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EFFECT OF FROST PENETRATION ON MOISTURE MOVEMENT IN SOLID WASTE LANDFILLS

UNIVERSITY OF ALBERTA.
University — Université

M. Sc.
Degree for which thesis was presented — Grade pour lequel cette thèse fut présentée

1984
Year this degree conferred — Année d'obtention de ce grade

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EFFECT OF FROST PENETRATION ON MOISTURE MOVEMENT IN SOLID WASTE LANDFILLS

THE UNIVERSITY OF ALBERTA

by

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EUGENE JACOB LESKIW

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF MASTER OF SCIENCE

IN ENVIRONMENTAL SCIENCE

DEPARTMENT OF CIVIL ENGINEERING

EDMONTON, ALBERTA

FALL, 1984

THE UNIVERSITY OF ALBERTA

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ABSTRACT

The effect of a temperature gradient on the process of moisture translocation within the landfill environment has not been studied in a cold-climate region. This concept is applied to a cold-room laboratory study investigating the translocation and possible accummulation of soil moisture through shredded municipal refuse subjected to a temperature gradient.

The laboratory study consisted of four series of experiments involving three test samples in each series. The test result parameters included water intake rate from a free source, moisture content profile, and temperature gradient. In all four series of tests there was a water intake rate to the sample which was attributable to the freezing process.

The paramater which is considered to characterize the relationships between the derived parameters of water intake rate and temperature gradient is segregation potential. The segregation potential is related to the suction force at the frozen fringe and is a function of the degree of thermal imbalance.

The significance of this transient moisture behavior over seasonal changes becomes apparent in the leachate production process within the landfill. Because of scale-up complexities, field investigations are necessary to verify this phenomena.

ACKNOWLEDGEMENTS

I would like to thank Dr. D. W. Smith for suggesting the thesis topic and for the invaluable help and guidance given during the study. I would also like to thank Dr. D. Sego for his contributions to this project, especially for his patience and understanding and for his continual support.

A very sincere thanks goes to Mr. G. Cyre and his staff for their assistance in setting up the laboratory apparatus.

I am grateful for the support and the joke sessions extended by my fellow graduate students, who at times provided their own insight into the exciting world of research.

I also wish to thank Ms. A. Ehrenholz for her help in preparing the final text of this thesis.

The City of Edmonton, Water and Sanitation Department staff at the Strathcona Transfer Station also deserve thanks for the assistance provided in obtaining refuse samples.

Finally, a very heartful thank-you to Mr. Ken Simpson, Waste Management Branch, Alberta Department of Environment who made all this possible by supporting my convictions towards post-graduate studies.

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1. INTRODUCTION

1.1 Background Information

Sanitary landfills presently play a significant role in the disposal of solid wastes in Canada. They will likely continue to do so because, in many cases, they enjoy an economic advantage over other means of disposal while at the same time providing an adequate and acceptable level of service. The sanitary landfill method of disposal emerged in response to problems associated with disposal of garbage such as open burning, disposal in wetlands, ravines, and streams, blowing of debris, and undesirable odors.

By definition, a sanitary landfill is a land disposal site employing an engineering method of disposing of solid wastes on land in a manner that minimizes environmental hazards. This is done by spreading the wastes in thin layers, compacting the solid wastes to the smallest practical volume and compacting a cover material overtop the waste.

At municipal waste generation rates of 1.6 to 1.8 kg per capita, Alberta produces a volume of 4000 tonnes of refuse each day. Being able to dispose of this waste in a manner not detrimental to the environment presents a major challenge to our society. Consequently, the impact of sanitary landfills on the environment has always been a subject of concern. As a result the scientific and engineering community has devoted much time and effort in trying to obtain a better understanding of some of the processes that relate to this waste disposal technology.

The production of leachate from municipal sanitary landfills is an important environmental problem associated with solid waste disposal. Generally, accepted landfill designs avoid placement of solid waste below the water table, preventing saturation of the landfill. In the unsaturated environment above the watertable, unsaturated flow in a porous media takes place. During this unsaturated flow, soil moisture typically becomes heavily polluted with soluble and suspended solids of organic and inorganic nature from the refuse. This leaching process takes place by intimate contact of the extracting liquid water with a partially saturated adsorbent and the polluting material is released by physical, chemical, and microbial processes (Straub and Lynch, 1982a). The resulting percolate is known as leachate.

If allowed to migrate freely from the landfill, leachate may pose a severe pollution threat to the groundwater. Johnson _et al._ (1981) analyzed samples of soil moisture in the unsaturated zone beneath three landfills and all indicated the presence of leachate contamination. In studies of landfills in Pennsylvania, Apgar and Langmuir (1971) concluded that improperly designed landfills located above the watertable in permeable materials can result in serious groundwater pollution. Cole (1972), Miller _et al._ (1974), Clark (1979) and others have reported cases in which leachate contamination has had harmful effects on groundwater aquifers. However, there are also many landfills at which problems have not occurred (Hughes _et al._ 1971, Farquhar and Rovers, 1972, Rovers and Farquhar, 1973).

Increased concern about such pollution has initiated efforts to develop a better understanding of the mechanisms of leachate production and its control. One of the major problems associated with the design, operation, and maintenance of landfills is the uncertainty of the dynamics of leachate production. These same uncertainties have made assessment of the pollution potential of existing or proposed landfills a problem.

A large number of factors interact to produce variable quantity and quality leachate from landfills. Many empirical investigations have been made into the process of landfill leaching. The goals of leachate generation studies have been to determine the volume and rate of leachate production, identify types and concentrations of pollutants present in leachate, and to observe relationships among climate, age, refuse placement, leachate production, gas generation, temperature, settlement, and overall landfill stabilization (Straub and Lynch, 1982b). These studies have utilized laboratory-scale columns filled with refuse as well as pilot or field scale landfills.

One area of uncertainty is the magnitude of these problems exerted by changes in climate and season. It is reasonable to speculate on the effect of temperature on leachate production in general terms only. Not only does temperature throughout the landfill affect the chemical and biological process, but physical processes also change.

Leckie et al. (1979) and others have found that there was an apparent thermal response of the upper part of landfill to the mean ambient temperature while the deeper materials tended to show a much smaller thermal response. The effect of a temperature gradient on the process of moisture translocation within the landfill environment has not been studied in a cold-climate region.

1.2 Scope of this Study

It is the objective of this study to learn more about the influence of surface freezing on leachate production within a landfill. This will be done by investigating the translocation and possible accumulation of soil moisture through shredded municipal refuse which has been subjected to a temperature gradient. This was accomplished using a frost cell in a laboratory cold-room environment.

During the decomposition of organic material within the landfill, energy is released in the form of heat by acid forming bacteria. The landfill can be considered a hot spot within the subsurface and, indeed, temperatures as high as 71°C were observed in a deep landfill in California (Emcon Associates, 1980). Mean ambient temperatures (monthly mean) vary seasonally and for Alberta a range of about 70°C over the annual cycle can occur. It is expected that there will be a pronounced thermal response over the depth of the landfill to this seasonal air temperature change. This is the basic mechanism of freezing of soils. Whenever a negative temperature gradient is imposed on a soil, heat is removed causing a drop in ground temperature. When enough heat has been removed and the ground temperature is 0°C, a freeze-front or the 0°C isotherm will be established. This freeze-front moves in accordance with the relative imbalance of heat removed from the bulk of the soil (Arvidson, 1973).

During the winter season, the surface of the landfill becomes cold with the frost-front penetrating to some depth beneath the surface. It is known that soil moisture migration is induced in the direction of the cold front by temperature-induced forces occurring somewhere within the freezing zone. It can be expected, therefore, that this mechanism will provide the driving force for moisture translocation within the refuse mass of a landfill. This translocation would be the addition of moisture from a free and available source such as the groundwater table. Under proper conditions of pressure and temperature, ice lensing may occur at the 0°C isotherm. The importance of this phenomena is the net addition of moisture to the refuse mass and the contribution of this moisture flux to the leachate production mechanism upon thawing of the refuse mass during the following spring and summer.

An experimental cell was used to simulate landfill conditions. Shredded municipal refuse was placed in three cells and compacted to a selected density. Initial moisture content of the refuse was varied and the sample was subjected to one dimensional heat flow conditions. The refuse was exposed to a water supply at the base of each cell.

In this study, the landfill is considered as a single, well-mixed reactor. Therefore, the assumptions of uniform, constant initial moisture content and well mixed refuse distribution are justifiable. Effects such as variable moisture storage, impermeable boundaries, and sources and sinks of moisture within the refuse mass are not developed. Actual behavior may be complicated by such non-ideal influences including channelling and short-circuiting (Straub and Lynch, 1982a).

2. LITERATURE REVIEW

2.1 Introduction

Soil, being non-homogeneous, possessing many properties is a complicated engineering material to work with and to research. The study of frost advance and moisture migration upon freezing and thawing in soils is simultaneously a geotechnical and heat transfer problem. Studies of this problem have generally been related to foundations and structures in an environment of seasonal freeze-thaw conditions.

The movement [illegible] water in a porous medium occurs under the action of total head differences, and is influenced by surface tension and other forces associated with the tendency for moisture to adhere to solid surfaces, notably water adsorption. In this respect, the shredded refuse material is considered to behave in a similar manner as soil in its moisture retention and transmission capabilities. There is one notable difference in that the refuse particles have a greater moisture absorptive capacity than the solid particles of a soil and would therefore have a greater capacity to store and retain moisture under similar conditions. The concepts, which form the basis for studying the aspects of flow through a porous media, remain unchanged. These concepts will aid in the methodological organization of the subject as well as in supporting an idea built on basic knowledge already available.

2.2 Heat Transfer Mechanisms in Soil

Heat flows from the soil during the freezing process due to the thermal gradient; that is, the ground surface is colder than the freezing front. The principal mechanism for heat transport in most engineering applications involving freezing and thawing is conduction (Andersland and Anderson, 1978). Conduction is the transmission of heat by the passage of energy from particle to particle or through the soil pore fluids.

The steady rate of heat transfer in a material by conduction is given by Andersland and Anderson (1978) as:

$$Q_c = -k(dT/dx)A \qquad (2.1)$$

where Q_c = heat flow per unit time, W (W = 1J/s)

k = thermal conductivity, (W/m)K

T = temperature, °K

x = distance, m

A = area, m^2

As shown by Equation (2.1) heat transfer due to conduction is directly dependent on the thermal conductivity, k, of the medium and the thermal or temperature gradient, (dT/dx). The time rate of change of the heat content depends on the temperature differential in the direction of heat flow and on the thermal properties of the soil (Andersland and Anderson, 1978).

Conduction is independent of mass-transfer processes. The effects of convection can also be accommodated in the application of analytical techniques developed from conduction theory to problems involving mass transfer. Convection is defined as the transmission of heat by mass movement of the heated particles (Andersland and Anderson, 1978). In porous earth materials, convection occurs both by the movement of water or other fluids contained in the soil pores and by the movement of air and other gases through the interconnected pore spaces.

The transport of water in unsaturated soil systems under the influence of a thermal gradient has been studied by Gurr et al. (1952) using salt tracers. The results showed that although some water circulation to the warm side by liquid diffusion did occur, the dominant transport mechanism under a thermal gradient at temperatures above 0°C is vapor diffusion to the cold side. The study also showed that vapor transfer is important quantitatively only in situations where there is a net gain or loss of water from the system due to condensation or evaporation. In most field situations in which the thermal gradient normally lies in the range of 0.01 to 0.1°C/m, thermally affected water transport at temperatures above 0°C is small and may be neglected without appreciable error (Andersland and Anderson, 1978).

The steady state heat flux per unit time due to convection is given by Andersland and Anderson (1978) as:

$$Q_{conv} = (C_0)(\rho)(V_0)(dT/dx)(A) \tag{2.2}$$

where Q_{conv} = convective heat flow per unit time, W/m
V_0 = fluid flow velocity in x direction, m/s
C_0 = specific heat of fluid, J/Kg·K
ρ = density of fluid, kg/m^3

and T, A, and x are as previously defined.

2.3 Factors Affecting the Thermal Conductivity of Soils

Thermal conductivity characterizes the ability of a material to transmit heat by conduction and is defined as the quantity of heat flow that will occur in unit time through a unit area of a substance under a unit temperature gradient (Andersland and Anderson, 1978). The thermal conductivity is independent of whether any fluids in the interstitial pores are in motion.

Soils are composed of solid, liquid, and gaseous matter. The thermal conductivity of a soil, therefore depends on the thermal conductivities of its components, their volume proportions, and their arrangement or structure (Andersland and Anderson, 1978).

In general, the thermal conductivity of soil depends on its density, water content, temperature, texture and mineral composition.

2.3.1 Temperature

The important aspect of temperature on the thermal conductivity of soils is whether the soil is frozen or unfrozen. The difference in conductivitiy of frozen and unfrozen soils is dependent on the difference between the conductivity of ice compared to water (Andersland and Anderson, 1978). Generally, both unfrozen and frozen soils with high moisture contents have a higher thermal conductivity than drier soils. On the basis of an average of a large number of tests, the conductivity of frozen soils does not vary markedly in a temperature range from -5°C to -35°C (Kersten, 1948). The conductivity at -35°C becomes somewhat greater than that at -5°C as the moisture increases. The same data also indicated that the conductivity of frozen soils (with a drop in temperature) increased more for a soil with a high density than with a low density. The foregoing facts may be explained by the conductivity of ice. The resultant effect is a function of amount of moisture present.

2.3.2 Soil Moisture Content

The moisture content of a soil has a very important effect on its thermal conductivity (Kersten, 1951). At a constant dry density, any increase in moisture results in an increase in thermal conductivity. The increase continues up to the point of saturation and holds for frozen as well as unfrozen soil. The rate of increase is about the same at all moisture contents.

2.3.3 Density

Tests have shown that an increase in the dry density of a soil, with the percentage of moisture remaining the same, results in an increase in thermal conductivity (Kersten, 1948). The rate of increase is about the same at all moisture contents and is not particularly different for frozen and unfrozen soils. As a general rule, it may be assumed for a given soil that a change in dry density of 5 g/cm^3 will result in a change of one percent in its thermal conductivity (Kersten, 1948).

2.3.4 Texture

If soils of different texture are tested at equal moisture contents and densities, it will be found that the coarse grained materials, such as gravels and sands, will have high conductivites; fine grained soils such as silt loams and clays, low conductivities and intermediate-textured soils values between these two (Kersten, 1948). Soils with high organic contents have the lowest conductivity. It should be noted that in the field, sandy soils ordinarily exist at higher densities and lower moisture contents than silt and clay soils.

Hence, the differences noted in the laboratory testing may not occur in soils in their natural state (Kersten, 1948).

2.3.5 Mineral Composition

Consideration of mineral composition has shown that this factor does have some effect on the thermal conductivity of a soil. In general, tests indicate that sands with a high quartz content have greater conductivities than sands with high contents of such minerals as plagioclase feldspar and pyroxene, which are constituents of basic rocks (Kersten, 1948). Soils with high contents of kaolinite and other clay minerals have relatively low conductivities. This may be due to the fine texture and is not necessarily the result of the presence of these minerals.

2.3.6 Structure

Soils in the field may have distinctive structure or laminations which may have a large effect on their conductivity. Smith (1939) found that for granular structured soils there was little, if any, differences in test results on undisturbed soils and on remolded and recompacted soils. For most structure patterns, however, conductivity values for the undisturbed materials are greater than those on the same soil after a breaking down of the structure. In some cases it was twice as great as that observed for the reduced state. In frozen soils, particularly those with ice lenses, the effect of stratification may be very important (Kersten, 1948).

2.4 Moisture Migration in Soils

The moisture equilibrium in soils is disturbed and the moisture goes into motion when physical forces arise in the soil, capable of making water migrate. Such forces may be caused by hydrostatic pressure gradients, capillary pressure, disjoining pressure of aqueous films, chemical potential and/or temperature.

It is the intent to study the relative importance of thermal moisture flow as compared to moisture flow under total head. This concept may be thought of as the moisture flux through soils which arises solely due to a temperature gradient. It is the translocation of moisture in the absence of osmotic, electrical, and pressure gradients.

The freezing process in soil and the heat and moisture transfer from warm regions to colder ones are very complex phenomena. Studies have shown that a variation in any one of the factors in the soil freezing process influences, to some extent, the properties of soil, water and ice. The entire soil-water-temperature system is influenced by the application of a thermal gradient.

Freezing of a soil system is brought about when a cold temperature is applied to the surface of the soil system. Upon the application of a freezing thermal potential, the upper part of the soil system freezes, after releasing the latent heat of the soil water. Across the soil system, from the top down, a curvilinear temperature gradient is established. Then, an upward heat transfer from a region of higher temperature towards a region of colder temperature takes place. Thermal energy, measured by work done across the porous soil system, starts the upward migration of soil moisture (Mageau, 1978).

The problem of moisture migration during the freezing of soils is of great importance; numerous investigators have studied this problem since the end of the nineteenth century. Several theories of moisture migration during soil freezing have been proposed to conform to the observed phenomena.

Following is a brief review of the basic theories of moisture migration during the freezing of soils.

Bouyoucos (1915) concluded experimentally that the transfer of water took place principally in the films of water surrounding the soil particles. He attributed this movement of liquid moisture to changes in the soil moisture tension (the suction force of the soil) which depends upon temperature. This concept was proposed to account for the processes that occur when ice crystallizes in freezing soils and is referred to as the "theory of crystallization forces" which supplemented the concept of film migration of water.

Smith (1939) held that water transfer was caused by the convection of water vapor and later considered that moisture movement under the influence of a thermal gradient was the result of a combined cyclical process of vapor condensation and local capillary flow.

Winterkorn (1943) developed a theory of film flow of liquid moisture from the hot to the cold end along the inner surface of a pore system as a result of the change in the adsorption energy of the soil particles as a function of temperature change. This concept is appropriately named the adsorption-film theory.

Winterkorn (1943) also observed the appearance of a difference of electrical potentials in the soil in the presence of a temperature gradient and suggested that the thermo-migration of moisture might be a specific case of electro-osmosis.

Field experiments were undertaken to try to quantify the magnitude of the transport phenomena put forth by the various concepts and theories. Cary (1966) presented sample calculations and suggested practical applications of thermal moisture flow as compared to flow under gravity head gradients. Ferguson, et al. (1964) studied soil water and temperature distributions in a silty clay loam soil under freezing winter conditions. Willis, et al. (1964) studied the water table change during the winter months created by the upward migration of moisture into the frost zone.

Finally, phenomenological theories of the migration of moisture in soils have recently come into rather widespread use. They are based on mathematically rigorous differential equations of heat and mass transfer. Some of the most recent investigators include Harlan (1973), Guyman et al. (1980), and Taylor and Luthin (1978), and Konrad (1980).

2.4.1 The Principle of Moisture Migration

Considering the experimentally established effects of various factors on the migration process, Tystovich (1975) put forth the following conclusion: "all of the motive forces of migration are functions of electromolecular forces of the soils." The mechanism of water migration during freezing of various soils may take a wide variety of forms, but in the final analysis, it reduces to the action of molecular forces of the mineral soil particles and the ice (Tsytovich, 1975).

With the experimental results brought forward in the thirty years that this phenomena has been studied, investigators have generally agreed on the principle in the following manner: "the migration of water in freezing moist soils is a process of moisture transport that operates consistently whenever the equilibrium state of the soil's phases is disturbed and external factors change (the presence of temperature, moisture content, pressure, mineral particle surface energy, mobility of molecules in water films, gradients, etc.)", Tystovich (1975).

This general formulation of the relationship that determines the migration of moisture in freezing soils provides a physical explanation for the various moisture migration mechanisms and incorporates all the basic conceptions in a definition of generalized migration forces. Therefore, the process of moisture migration can begin only on a disturbance of the equilibrium state of the phases of the soil, since migration of moisture will not occur in soils when they are perfectly homogeneous and under isothermal conditions in the absence of external disturbances (Tsytovich, 1975).

All of the factors that have been identified in experiments and field observations as influencing moisture migration in freezing soils are explained quite satisfactorily by this migration principle.

Finally, the migration of water in frozen soils, which is possible only in the presence of unfrozen water retained by adsorption on the surfaces of soil mineral particles, is subject to the same laws of film-water motion that were established for soils at positive temperatures, but has its own pecularities because of the additional effects of ice crystallization forces (Tystovich, 1975). In this case, the migration process of the film water will be very slow.

2.4.2 Motive Forces of Water Migration in Non-Saturate Systems

Water migrates in freezing soils under the influence of various forces, which determine the prevalence of one moisture-transfer mechanism or another. The following are forces which have been presented in the literature and summarized by Tsytovich (1975):

1. water vapor pressure forces (more important in soils with low-moisture contents);
2. pore-water capillary forces (a secondary effect of the action of adsorption forces and in the process of water migration in freezing soils, govern the capillary-film mechanism at attainable water table depths shallower than the depth of maximum capillary rise);
3. external and internal pressures, including vacuum;
4. osmotic forces (become dominant and determine migration only when the pore water contains substantial amounts of solutes);
5. ice crystallization forces (they become important in the process of segregation and accumulation of ice at the freezing front, continually adding new portions of migrating water to the ice deposits that have already formed and strongly enhancing the adsorption-film mechanism of migration); and
6. adsorption forces arising from the organic/mineral skeleton of the soil and ice, arising under the influence of the free surface energy of the mineral particles.

Migration forces cause motion of pore water in freezing soils only when phase equilibrium is disturbed and conditions are created for the appearance of various gradients: moisture, temperature, adsorption-film, osmotic and other pressures.

Tystovich (1975) has in the general case written the following equation for the migration water flux:

$$i_{mig} = -k \text{ grad } F \qquad (2.3)$$

k = a proportionality coefficient characterizing the specific resistance offered by the soil system to motion of the moisture.

F = a generalized motive force.

This equation determines the flux of migration water along the generalized-force gradient, to which it is directly proportional.

Any of the migration forces referred to above can be taken as the generalized force and it follows that the case of the generalized force to be used must be determined by experimental study (Tystovich, 1975).

2.4.3 Local Entropy Production in Transport Processes

Natural transport processes, like all irreversible processes, derive their spontaneity from a degradation of energy from a higher ordered form to one of a lower degree of ordering (Groenevelt and Bolt, 1969). In thermodynamic language, this implies a production of entropy. It appears that this entropy production accompanying transport processes may be expressed as a sum of products of independent fluxes with their conjugated driving forces. The expression for the entropy production in a system is found from a combination of the Gibbs equation of thermostatistics with conservation equations. Groenevelt and Bolt (1969) have developed a combination of Gibbs equation with appropriate conservation equations to yield an expression for the local production of entropy (i.e. energy dissipation) accompanying the flow of heat and mass. The equation yielded three components, viz. the dissipation of energy accompanying:

1. the flow of heat;
2. the diffusion of solutes through water; and
3. the viscous flow of the solution through the matrix of the porous medium.

Darcy's law which assumes isothermal conditions is used extensively to describe the flow of soil moisture; however, under field conditions diurnal and seasonal temperature fluctuations at the soil surface induce water and heat movement at depth in the soil.

Moisture flows through soil from warmer to cooler areas in both the vapor and liquid phases. Most of the early studies on water movement in soils due to external gradients indicated that the transfer occurred in the vapor phase. It was thought to be primarily a molecular diffusion process which was described by Philip and de Vries (1957) as the "series-parallel" theory based on Darcy's law and Fick's law with modification to account for the presence of a temperature gradient. Winterkorn (1958) and Taylor and Cary (1964) developed the theory of "irreversible thermodynamics" which requires no assumptions regarding the nature of flow process. Dirksen and Miller (1966) and Cary (1966) using experimental work concluded that moisture movement due to temperature gradients was insufficient to account for upward water movement and that moisture flow in the unfrozen soil was caused by events taking place in the frozen portion of the soil. The equations obtained from the theory of thermodynamics of irreversible processes were, therefore, considered inadequate for the complex and transitory processes involved in these experiments.

The flow of moisture in thin films or through small capillaries under the influence of a thermal gradient is not well understood. There are at least four possible reasons why water flows in the liquid phase under the influence of a thermal gradient (Cary, 1966):

1. Since the surface tension of water against air increases as the temperature drops, moisture in unsaturated soil could flow from warm to cool under the influence of a surface tension gradient.
2. Soil moisture suction increases with temperature drop and may contribute to the moisture flow. This is the basis for the thermally induced liquid flow equation developed by Philip and de Vries (1957). Deryaguin and Melnikova (1958) also developed an analysis based on surface tension gradient. However, as a second possibility, they also considered the difference in specific heat content between the liquid layer adsorbed on the solid surface and the specific heat content of the bulk of the liquid in the pores as creating flow from cool to warm areas.
3. Transfer from warm to cool results from a net motion generated by random kinetic energy layers associated with the hydrogen bond distribution which develops under a thermal gradient.
4. Flow results from thermally induced osmotic gradients. Most

dissolved salts will spontaneously diffuse through a solution from warmer areas into cooler areas (Soret effect).

2.4.4 Mechanism of Soil Moisture Transfer During Freezing

The physical nature of thermal moisture migration is primarily associated with the effect of temperature on water vapor tension and the potential of the liquid phase (Jumikis, 1956a). Basically, soil moisture can be transported upward through the porous medium of soil upon freezing as:

a) a vapor;
b) a liquid (bulk or film); or
c) a liquid and vapor.

Vapor Transport

In a dispersed system which soil is, moisture can be transported upward from the groundwater by way of vapor diffusion if the voids are relatively large and there is no continuous moisture in the liquid form in the voids connecting the groundwater with the downward freezing front. The driving pressure is the vapor pressure difference between the partial vapor pressure at the warmer end (the groundwater surface) and the partial vapor pressure in the upper region of the soil system just below the freezing front where it can be very small or even negligible as compared with that at the warmer surface (Jumikis, 1956c). This difference in partial vapor pressures results from a difference in temperature at the bottom and top of the freezing system. There might be a vapor pressure difference in soil due to a difference or variation in capillary moisture surface tension (Jumikis, 1956c). The weaker or stressed part of capillary moisture which is located farthest from the soil particle may merge with that adsorbed to the surface of an adjacent soil particle. This merger can under certain circumstances be interrupted by the formation of vapor or gas bubbles. Thus, diffusion and condensation would take place in the freezing soil system.

The phenomena of upward diffusion of soil vapor is analogous to diffusion of one gas through another gas i.e., water vapor and air (Jumikis, 1956c). This problem can be treated by Fick's first law of diffusion. In this law it is assumed that the diffusion of matter is analogous to the heat transfer in the steady state through a slab according to Fourier's law, the difference being that the coefficient of gas (vapor) diffusion takes the place of the coefficient of the thermal conductivity. Generally, this is stated by Jumikis (1956c) as:

$$W = (-D)(A)(dc/dx)(dt) \qquad (2.4)$$

W = quantity of substance in grams diffused during time, t, through area, A

D = constant of proportionality in cm^2/sec.

A = cross sectional area, cm^2

dc/dx = concentration gradient

c = concentration of diffusing substance given as amount of substance per cm^3.

x = coordinate perpendicular to a reference plane or distance in cm, along the path of diffusion.

D is the coefficient of diffusion for one gas to another gas. The minus sign indicates that diffusion take place from a region of higher concentration to one of a lower concentration.

Jumikis (1956a) concluded that soil temperature below the frozen layer does not vary appreciably. Consequently, vapor pressures during the freezing season are not of great magnitude, nor do they vary appreciably. Jumikis (1956a) felt that this mechanism of transport is probably more pronounced in spring and fall when temperatures change more rapidly.

The intensity of vapor diffusion in soil will vary with soil texture (Jumikis, 1954). In soils with large voids (function of coarse soil particles and loose packing) vapor diffusion would be more effective than in soil with small voids.

If a soil is fully saturated with water, vapor phase transport of moisture cannot occur since there would be no sites for condensation. If there is no groundwater present, the soil freezing will be essentially a drying process until all of the soil moisture has been transferred into the freezing zone (Jumikis, 1954).

Film Transport (Bulk)

In a dense soil, i.e., close packing of the particles (small porosity), the moisture around and between the soil particles may form uninterrupted films through the entire soil system down to the ground water supply. Depending on the texture of the soil then, the film transport process may be most effective in relocating moisture to the freezing front. The freezing front or ice lens is thus connected via the moisture film at the ice surface and via the soil moisture films with the source of ground-water supply (Jumikis, 1954). The driving pressure is the pressure difference between two points affected by (Winterkorn, 1958):

1. hydrostatic potentials;

2. potential due to the hydration energy of ions, relating to the heat of wetting;
3. potential due to the osmotic energy of ions either held in equilibrium on the solid particle surfaces or free in the aqueous solution; and
4. thermal gradients affecting the thermal-viscous flow of the film.

The film seems to be two-dimensional, that is, it is immobile perpendicular to the surface of the soil particle, but is mobile parallel to the surface. The movement of the film moisture is hence by a slip, by overcoming the shearing resistance of the liquid (Jumikis, 1954).

The amount of moisture transferred by means of film flow should be proportional, among other things, to the specific surface area of the soil particles in a unit of volume. The increase in density of the soil means more soil particles packed within a unit of volume, which in turn means more specific surface, more moisture film, and consequently more film moisture transferred (Jumikis, 1954).

Film Capillary Transport

If the state of packing is such that the soil moisture can occupy absolutely all voids, then upon freezing, an upward motion of film-capillary soil moisture from the ground water table takes place. The driving pressure for the upward capillary moisture flow is the difference in the vapor pressure at the ground water surface and the one at the curved surfaces or menisci at the freezing ice lens, plus the flow pressure (molecular, or viscous or both) caused by the molecular motion of the warmer particles of water upward from the ground water surface toward the cold front (Jumikis, 1956b).

Upon moisture redistribution, the thermal properties (conductivity and diffusivity) of the moist soil change, hence do the driving potentials.

Upon formation of ice at the isothermal surface of the frozen soil layer, latent heat is set free and the temperature at the downward-progressing freezing isothermal surface enables the existence of a non-crystalline film of water which is stable even below the freezing point. This liquid-water film is thought to be in equilibrium with its vapor phase on one side and with the ice crystal on the other side (Jumikis, 1956c).

Film-capillary transport, assumes that the ice lenses are connected via the ice water films and further via the soil moisture films and capillary moisture (if it exists) with the ground water (Jumikis, 1956c).

Combination of Transfer Mechanisms

Depending upon the texture and gradation of the soil, the degree of packing, stratification, degree of saturation, thermal properties of the soil, a combination of the various soil moisture transfer mechanisms may exist simultaneously upon freezing (Jumikis, 1954). There are no sharply defined boundaries between the various modes of transport mechanisms and processes. It is reasonable to assume, therefore, that a transition from one mode to another constitutes the combination of mechanisms which may exist at a particular time interval.

2.4.5 The Freezing Process - Summary

When a temperature below freezing is applied to the surface of a soil sample, a thermal imbalance is created and transient heat flow is initiated. The freezing front progresses into the soil as a function of the imbalance of the heat supplied to the heat removed. Under fixed thermal conditions with time, the temperature distribution is assumed to be linear. In laboratory tests by Mageau (1978) and Konrad (1980), measured temperatures reveal this, confirming one dimensional heat flow. Radial heat flow from the sample would distort this linear temperature profile. Also, in reality, the thermal conductivities of the frozen and unfrozen zones of the sample would vary, therefore affecting the temperature gradients.

Konrad (1980) in his preliminary investigations on frost heave phenomena established an active and a passive zone in the whole freezing system. The passive zone was described as the frozen soil. The active zone was composed of the frozen fringe and the unfrozen soil. The frozen fringe was defined as a zone immediately behind the frost line (i.e., 0°C isotherm) where soil water may accumulate and ice lens formation would take place (Konrad, 1980).

In applying this definition of the freezing system to the present investigation, Figure 2.1 illustrates the relationship between the temperature profile and the different zones. The temperature distribution has two important effects. It affects the temperature gradient in the frozen fringe and the length of the unfrozen soil.

The transient heat flow period is characterized by an advancing freeze front. In soil columns pore water freezes in-situ with the onset of nucleation of ice crystals. The ice crystals grow in the

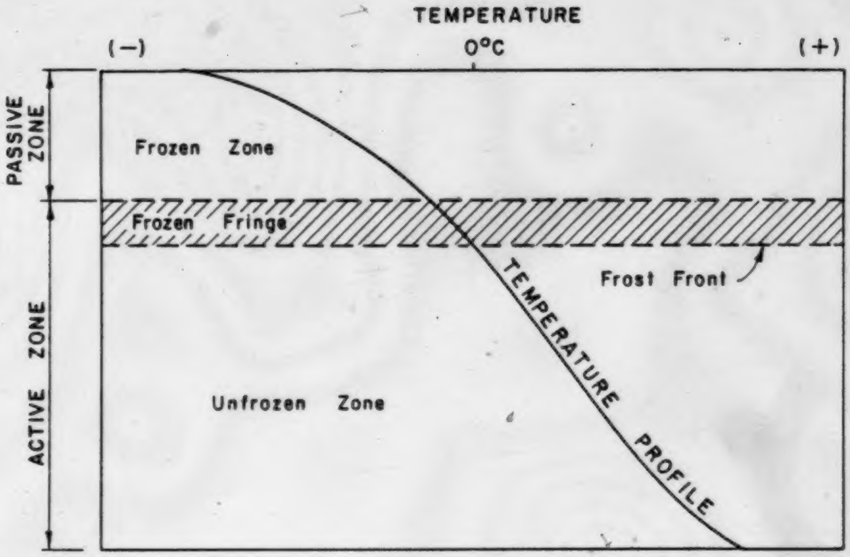

TEMPERATURE
(−)
0°C
(+)
PASSIVE ZONE
Frozen Zone
Frozen Fringe
Frost Front
TEMPERATURE PROFILE
ACTIVE ZONE
Unfrozen Zone

FIGURE 2.1 . SOIL FREEZE ZONES .

direction of heat removal. With in-situ freezing as well as freezing of additional water drawn into the sample, the latent heat of phase change results in a release of heat and an imbalance in the thermal equilibrium. Restoration is achieved by further freezing of the unfrozen soil resulting in an advance of the frost line (Konrad, 1980).

The water drawn into the active zone of the sample will flow into an accumulated zone whose location is controlled by local material permeability. In the case of the refuse columns, some of this water will be absorbed by the material as well, therefore there may be very distinctive zones or sinks of moisture accumulated throughout the active zone.

For a given freezing condition, the freezing characteristics of a given soil under zero applied pressure have been defined by Konrad as the segregation potential which is a function of the suction at the frost front, and the rate of cooling of the frozen fringe. The suction potential at the freezing fringe is considered as the driving force for water migration.

Mageau (1978) conducted frost heave tests on uniformly frozen Devon silt to study moisture migration characteristics of the frozen soil. He suggested that the dominant suction pressure develops in the frozen fringe. Mageau (1978) observed significant changes in water content in open system tests with no pre-made ice lens while very little migration of water appeared to have occurred behind a pre-made ice lens. Hoekstra (1969) concluded also that an ice lens acts like a cutoff with regard to water migration into the frozen soil.

Although other theories of moisture migration in freezing soils have been advanced, this phenomenological concept will be applied in the analysis and interpretation of results for this study.

Another significant factor is the relation to moisture migration in freezing soils of the permeability of the frozen soil. This permeability is related to the unfrozen water content which is a function of temperature and pressure (Harlan, 1973). Qualitative considerations reveal that the permeability decreases with decreasing temperatures as a direct consequence of changes in the unfrozen water content of the soil (Konrad, 1980). Konrad demonstrated that there was a distinct relationship between the average permeability of the frozen fringes and the suctions at the frost front (for a quasi-steady state condition).

The suction at the frost front can be estimated by the product of water intake flux and length of the unfrozen soil (Konrad, 1980). Aguirre-Puente et al. (1973) measured the suction at the frost line by extrapolating tensiometer readings in the unfrozen zone.

Konrad states that during a laboratory freezing test, the suction at the frost front continually changes. Initially, the relatively long flow paths in the unfrozen soil associated with high flow velocities give rise to quite high suctions at the frozen-unfrozen interface. The high flow velocity is contributed to rapid frost front penetration and to changes in the frozen fringe thickness as the temperature gradient in the frozen zone decreases. With time the length of unfrozen soil decreases as does the water flux leading to decreasing suctions at the frost line (Konrad, 1980).

As long as the relation between suction and frozen fringe permeability is such that the water flow entering the fringe is able to traverse it, water will be drawn into the frozen zone contributing to ice crystallization in the void spaces. The level of accumulation will be governed by the permeability in the frozen zone as well as changes created in the thermal balance resulting in ice crystallization and enrichment in this zone.

The concepts put forth by Konrad in modelling and characterizing a freezing soil at the quasi stationary frost front demonstrate two basic parameters - the segregation potential and the suction at the frost front. The relationship between derived parameters is accounted for by these two basic parameters.

2.5 Characteristics of Municipal Refuse

Municipal solid waste is defined as domestic and commercial waste generated in households, office buildings and non-industrial commercial establishments. Municipal solid waste is comprised principally of paper, food wastes, garden wastes, glass, metals, plastics, rubber and textiles. The breakdown of materials in Table 2.1 is representative of the variability of municipal waste components (Emcon Associates, 1980). Table 2.2, (Moell, 1980) also gives a physical analysis of waste entering the privately operated Genstar (formerly Consolidated Concrete) landfill in northwest Edmonton.

Indices commonly used to describe a sample of refuse include moisture content, bulk density, and dry density. Collectively, the components of municipal refuse will yield moisture contents of 15 to 60% on a wet mass basis, depending on the exact mix and climate.

Bulk densities of refuse may vary from 120 to 300 kg/m^3 as delivered to between 600 to 1200 kg/m^3 compacted. Relative to soil bulk densities which may under natural conditions be as high as 2200

Page 30

Table 2.1 (Emcon Associates, 1980) has been removed from the text due to copyright restrictions. It presents a physical analysis of municipal refuse components.

Page 31

Table 2.2 (Moell, 1980) has been removed from the text due to copyright restrictions. It presents a physical analysis of municipal refuse components.

kg/m^3, it is obvious that refuse is extremely porous and has a low specific gravity.

Dry density is frequently used in reference to bulk or total density relationships to be consistent with soil mechanics. There is difficulty in drying the samples thoroughly to yield representative water contents without burning off the organic materials.

2.5.1 Composition of Municipal Refuse

Refuse composition directly affects the rate of decomposition within a landfill cell.

Several studies have analyzed the chemical composition of typical refuse components and a summary is presented in Table 2.3, (Emcon Associates, 1980). The data is given as the percent of total wet mass of refuse. The data reveal that approximately 70 to 80% of the total wet mass is comprised of organic based materials.

Moisture content of refuse at the time of placement varies, and values between 20 to 35% have been reported most frequently in the literature. Table 2.4 shows moisture content of refuse components reported by a number of studies (Emcon Associates, 1980). As expected, food and garden wastes - the most rapidly decomposable fraction of refuse, contain the highest percentage of moisture averaging over 50% moisture on a wet weight basis.

The food and garden waste categories are of major significance with respect to leachate and gas generation. Moreover, other than rainfall and groundwater intrusion, it is from this fraction that the greatest contribution of moisture in the solid wastes is derived.

Pages 33-36

Table 2.3 (Emcon Associates, 1980) has been removed from the text due to copyright restrictions. It presents the chemical composition of municipal refuse components.

Page 37

Table 2.4 (Emcon Associates, 1980) has been removed from the text due to copyright restrictions. It presents moisture content of municipal refuse components.

2.5.2 Decomposition of Refuse

Extensive discussions considering possible reactions for the formation of acids and gases during refuse decomposition are presented in the literature.

Actual reactions can seldom be described by simple equations as those used for illustrative purposes. The decomposition reactions become more complex than the simplified equations indicate because of the formation of relatively small amounts of a variety of end products and the formation of these minor products will vary with the micro organisms present, and often with pH and temperature within the refuse mass.

2.5.3 Temperature

The characteristic temperature pattern of disposed refuse is a comparatively rapid increase to a maximum temperature followed by a slow decline which then fluctuates with the ambient air temperature. The rapid temperature increase is considered to be a result of the initial aerobic decomposition which produces a high rate of heat generation. For those studies that have reported elevated temperature, most increases in temperature have been short-lived ranging from a matter of weeks to months depending upon circumstances and operating conditions (Pohland and Engelbrecht, 1976).

Temperature has been monitored in several simulated landfill studies. Mertz and Stone, (1968) reported maximum temperatures in two simulated landfills of 49°C which decreased to a relatively constant temperature, reflective of seasonal effects, i.e., to 16°C and 12°C in winter and 32°C and 31°C in the summer. Accordingly, temperature fluctuations within a landfill will respond to normal ambient and seasonal conditions as moderated by the surrounding soil environment.

As aerobic conditions are replaced by anaerobic, the temperatures within the landfill decline. In leachate and gas production test cells in the Edmonton area, temperatures ranged from 27°C in July 1977, to a minimum of 5.5°C in June 1978 near the bottom of the cell (Moell, 1978).

2.5.4 Moisture

Moisture content of landfill materials is perhaps the most important in-situ factor affecting the quantity and quality of leachate ultimately produced. Sources of moisture include: infiltration water due to precipitation or groundwater, water content of initial refuse, artificially added water, and metabolic water formed during decomposition. Where percolation of water into the refuse mass is minimal, the water from decomposition may be the major source of leachate.

2.5.5 Moisture Retention by Refuse

The moisture retention, or absorptive capacity, of the refuse becomes a controlling factor in determining the magnitude of moisture flux through the refuse mass. The refuse is able to maintain a certain quantity of moisture in addition to the initial moisture content. This retention quantity can be determined when the initial refuse moisture plus the moisture added causes gravity drainage. This quantity is termed "field capacity" and is defined as the maximum moisture content which a soil (or solid phase) can retain in a gravitational field without producing continuous downward percolation. The concept of field capacity can be applied to compacted refuse (Fenn et. al. 1975).

Walsh et al. (1981) investigated moisture balance and leaching in a series of test cells. The data suggested that the attainment of field capacity was dependent upon the moisture retained. The time it took to reach field capacity did not appear to have any direct relation to either the moisture application rate or initial moisture content.

Generally, if compacted refuse is assumed to have an estimated moisture content of 30% by volume and a field moisture capacity of 50%, it would mean that one metre of buried refuse would absorb an estimated 200 mm of infiltration before a leachate would be produced.

2.6 Concepts and Techniques Describing Leachate Generation

2.6.1 Introduction

Leachate is generated as a result of water or other liquids infiltrating a landfill's soil/refuse layers and thereby percolating through the solid waste and picking up contaminants. The source of this water can be precipitation, surface runoff, co-disposed liquids, water of decomposition, and groundwater intrusion.

A variable quantity and quality of leachate is produced by the interaction of such factors as annual rainfall, runoff, infiltration, evaporation, transpiration, freezing, mean ambient temperature, waste composition, waste density, initial moisture content, and depth of landfill (Leckie et al. 1979).

The prediction of leachate generation in landfills is the key to the design of adequate landfill liners, cover materials, grading, filling sequence, leachate collection and treatment facilities, etc. to prevent ground and surface water contamination.

2.6.2 Water Balance Method of Leachate Prediction

There have been numerous mathematical models used for quantitative estimation of the volume of leachate generated from landfills and although these approaches vary, they rely upon the Water Balance Method or water budget principles. This method was devised by Thornthwaite and Mather in 1955 as reported in U.S. Environmental Protection Agency Report (Fenn et al. 1975). The climatic water balance refers to the balance between the income of water from precipitation and the outflow of water by evapotranspiration and runoff, with the excess being available to replenish soil moisture storage or as infiltration. Other contributors, or income include the water of decomposition, the initial moisture content of the solid waste, and infiltration of groundwater. Relative to the infiltration fraction of precipitation, the latter contributors have been considered negligible for a properly sited and designed landfill. The water balance method is based on:

1. a one-dimensional flow model and conservation of mass relationships among various components of the leachate sources, and;
2. the retention and transmission characteristics of the refuse and cover soil.

The generalized water balance relationships are shown in Table 2.5 (Lu et al. 1981). Water contributed by precipitation (W_p), surface runoff (W_{sr}), or irrigation (W_{ir}) will either become surface runoff (R), or infiltrate into the cover soil (I). A portion of the infiltrated water leaves by evapotranspiration while a portion will recharge the cover soil. Once the field capacity of the cover soil is reached, vertical percolation (PER_s) will occur. The quantity of percolation through the cover material can be calculated by using equation (2) in the table. At first the percolate will be absorbed by the refuse. As the landfill refuse reaches field capacity moisture content (estimated at 30% by volume), refuse percolate (PER_r) is generated in quantities described by equation (3) in the table. The percolate will eventually evolve as refuse leachate (L). If groundwater intrusion (W_{gw}) occurs, leachate generation estimates can be modified using equation (4) in the table. The relationships are shown in Figure 2.2 (Lu et al. 1981).

Precipitation and evapotranspiration are governed by different climatic factors and as a result are not often the same in amount or distribution through the year. Computation of the water balance is laborious and the data using mean monthly precipitation and evapotranspiration is available for all climatic stations from the Atmospheric Environment Service of Environment Canada. The assumptions in this method have been modified for Canadian conditions (Phillips, 1976); in particular, the calculation of recharge/runoff from snowfall and spring thaw. An example of the information for Camrose, Alberta is shown in Table 2.6. The information is plotted on a mean monthly basis as shown in Figure 2.3 (Moell, 1982). It is considered that applying

Page 43

Table 2.5 (Lu. et al, 1981) has been removed from the text due to copyright restrictions. It presents a generalized water balance equation for a municipal landfill.

Page 44

Figure 2.2 (Lu. et al, 1981) has been removed from the text due to copyright restrictions. It depicts the generalized water balance relationship at a municipal landfill.

Pages 45-46

Table 2.6 (Philips, D.W., 1976) has been removed from the text due to copyright restrictions. It presents climatic data used in the Thornthwaite climatic water balance.

Page 47

Figure 2.3 (Moell, 1982) has been removed from the text due to copyright restrictions. It is a plot of water balance information for the Camrose, Alberta region.

mean monthly data to the water balance method diminishes the importance of discrete events such as spring thaw and summer storms which are the main sources of infiltration and groundwater recharge from precipitation (Fenn et al. 1975).

In reality, infiltration - flow systems are much more complex than can be expressed with a simple physical equation. Field data measuring percolation rates must be obtained for the same conditions as will occur for the infiltration system being predicted with the equation. Values of precipitation and evapotranspiration are normally the most accurate data used in the water balance. Values for surface runoff, infiltration, soil moisture storage, refuse moisture storage, and water of decomposition are speculative, based on empirical, rational or experimental methods or engineering judgement. It is logical therefore, to assume the accuracy of this method would be poor. Lu et al. (1981) conducted a study in which different methods of calculating runoff, potential evapotranspiration, soil moisture storage, and infiltration were used. The study found that errors in the methods used in the Water Balance Method ranged from 1.32 to 5389%. The best that could be expected was possibly less than 100% error. The study suggested that much of this error may be due to limited field data from existing landfills or to the fact that most of the methods used were originally developed for other purposes and may not be suitable for landfill conditions.

3. LABORATORY TESTING PROGRAM

3.1 Testing Program

The objective of the program was to study the change in moisture content within samples of shredded municipal refuse to which a temperature gradient was applied.

The testing program consisted of four series of open system experiments (i.e., free access to water). Each series consisted of three test samples. The variables which were studied included temperature gradient across the sample, the sample density and initial moisture content. The water intake was measured daily. In all experiments, the vertical moisture flux was by unsaturated flow into the refuse sample.

3.2 Description of Equipment

The experimental apparatus utilized in this study is a frost cell designed for controlled temperature conditions. A schematic diagram of the equipment for a freezing test is given in Figure 3.1. Details of the cell are shown in Figure 3.2. Construction specifications are available in Hill (1977), Mageau (1978) and Konrad (1980). At the beginning of this investigation, one freezing cell was available. Two other cells were constructed with a slight modification to the base by omitting the pedestals.

The experimental set-up was designed for one dimensional freezing of the sample. The freezing cells were placed in a controlled temperature room maintained at a constant temperature of approximately +5°C. The use of a cold room minimized radial heat flow into the

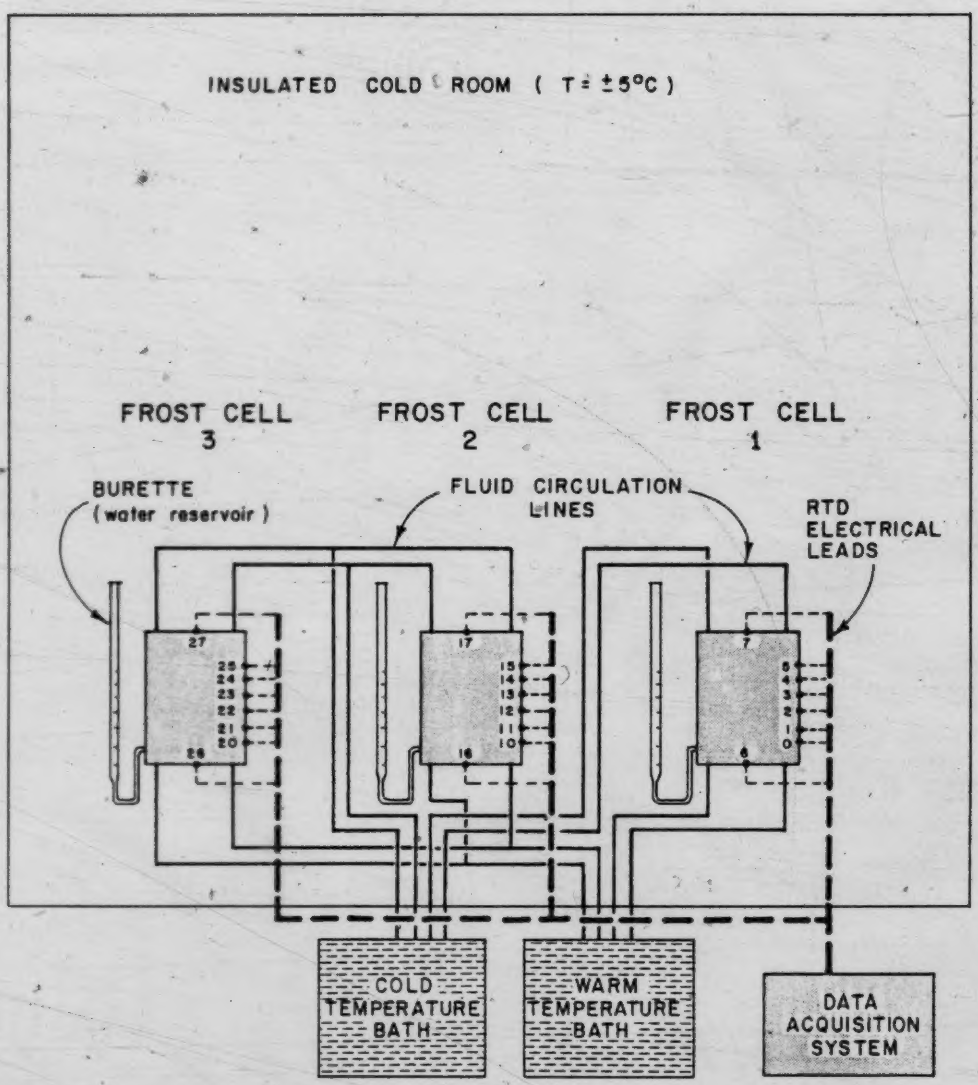

INSULATED COLD ROOM (T = ±5°C)
FROST CELL 3
FROST CELL 2
FROST CELL 1
BURETTE (water reservoir)
FLUID CIRCULATION LINES
RTD ELECTRICAL LEADS
27
25
24
23
22
21
20
26
17
15
14
13
12
11
10
16
7
5
4
3
2
1
0
6
COLD TEMPERATURE BATH
WARM TEMPERATURE BATH
DATA ACQUISITION SYSTEM

FIGURE 3.1 . SCHEMATIC DIAGRAM OF EXPERIMENTAL SET-UP .

Page 51

Figure 3.2 (Mageau, 1978) has been removed from the text due to copyright restrictions. It is a schematic of a cutaway view of the frost cell.

refuse sample. Figure 3.3 shows the experimental set-up in the cold room.

The freezing cell is a 100 mm inside diameter teflon lined cylinder. The outer jacket is machined P.V.C. pipe which acts as an insulator and also provides lateral restraint during the application of a vertical load. A rubber foam insulating jacket of 15 mm thickness was fitted around the outer wall of the P.V.C. pipe to provide additional insulation. Figure 3.4 shows a freeze cell during testing.

The top piston was used as a heat sink through which a glycol solution from the constant temperature cold bath was pumped. It was also used to transmit a pressure to the freezing sample by means of a hanger-weight assembly. The piston also allowed the measurement of volume changes occurring from heave since it slides freely within the cell. The relative position of the piston from the top of the P.V.C. pipe was recorded using a vernier caliper. The distance between these surfaces was measured to the nearest 0.01 mm and recorded. This enabled a check on piston movement caused by sample volume change.

The base plate was used as a heat source through which a glycol solution from the warm temperature bath circulated. The fluid temperature was maintained by separate hotpack constant temperature baths. These are shown in Figure 3.5. The baths have a pumping rate capacity of 80 mL/s. Such a high rate of pumping minimizes temperature fluctuations at each constant temperature plate. Circulation lines were insulated using 12 mm I.D. sleeve foam insulation with a 10 mm wall thickness, and foam tape insulation wrap to further reduce temperature fluctuations.

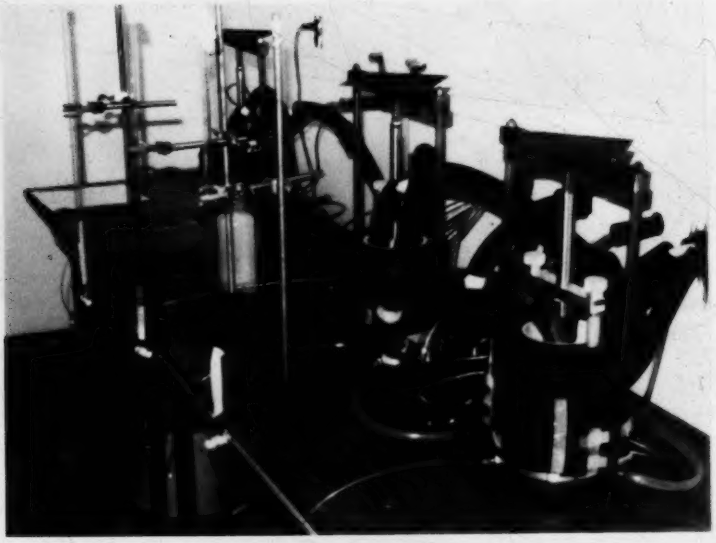


FIGURE 3.3 EXPERIMENTAL SET-UP IN COLD ROOM

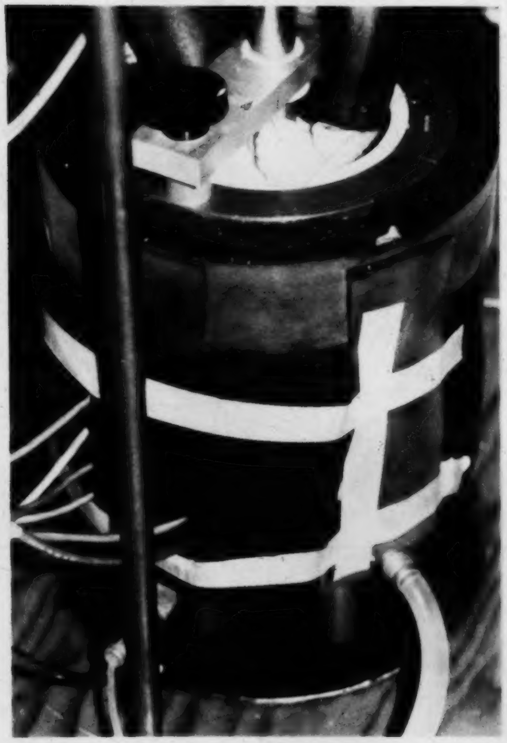


FIGURE 3.4 FREEZE CELL DURING TESTING

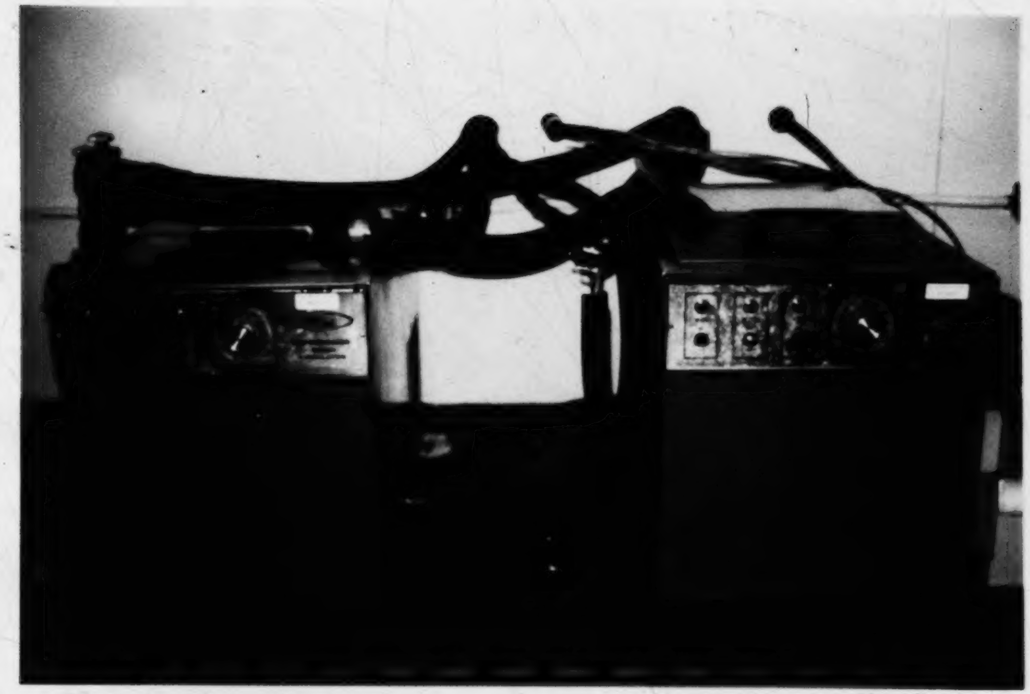


FIGURE 3.5 TEMPERATURE BATHS

An external source of water was made available from a burette to the sample at the bottom through a sintered steel porous stone set into the base. The configuration is shown in Figure 3.6. The volume change in the burette is calculated by measuring the change in water height from a reference point. This reference point was chosen separately for each cell so that approximately 10 mm of head above the porous stone was provided. This insured that the base of the freezing sample was in constant contact with water. Initially, measurements were taken as often as four times per day, decreasing to daily observations. The volume change in the burette can be obtained usually within ±0.1 ml. Water was added to each burette to the reference point level, if required, at each observation.

The temperature sensing devices used for monitoring refuse, top and bottom plate temperatures in the three freezing cells were platinum resistance temperature detectors (R.T.D.). Five were installed at the side of the freezing cell and one at each heat exchanger plate. The advantages of the R.T.D. are a small sensing tip, rapid response time of the thermocouple, and fair accuracy. The same calibration procedure as for thermistors has been adopted. The R.T.D.'s were encased by epoxy in 3 mm diameter holes drilled into the wall of the cylinder. The devices were then fitted with a Swedg-Lok fitting. The R.T.D.'s installed into the sidewalls were spaced at 10 mm, 20 mm, 30 mm, 50 mm, and 70 mm distances from the base for Cell 1 and 15 mm, 30 mm, 40 mm, 50 mm, 70 mm, and 85 mm distances from the base for Cells 2 and 3. The configuration is shown in Figure 3.7.

A Fluke data acquisition system employing a digital voltmeter was used to record the data from the R.T.D.'s. Figure 3.8 shows the

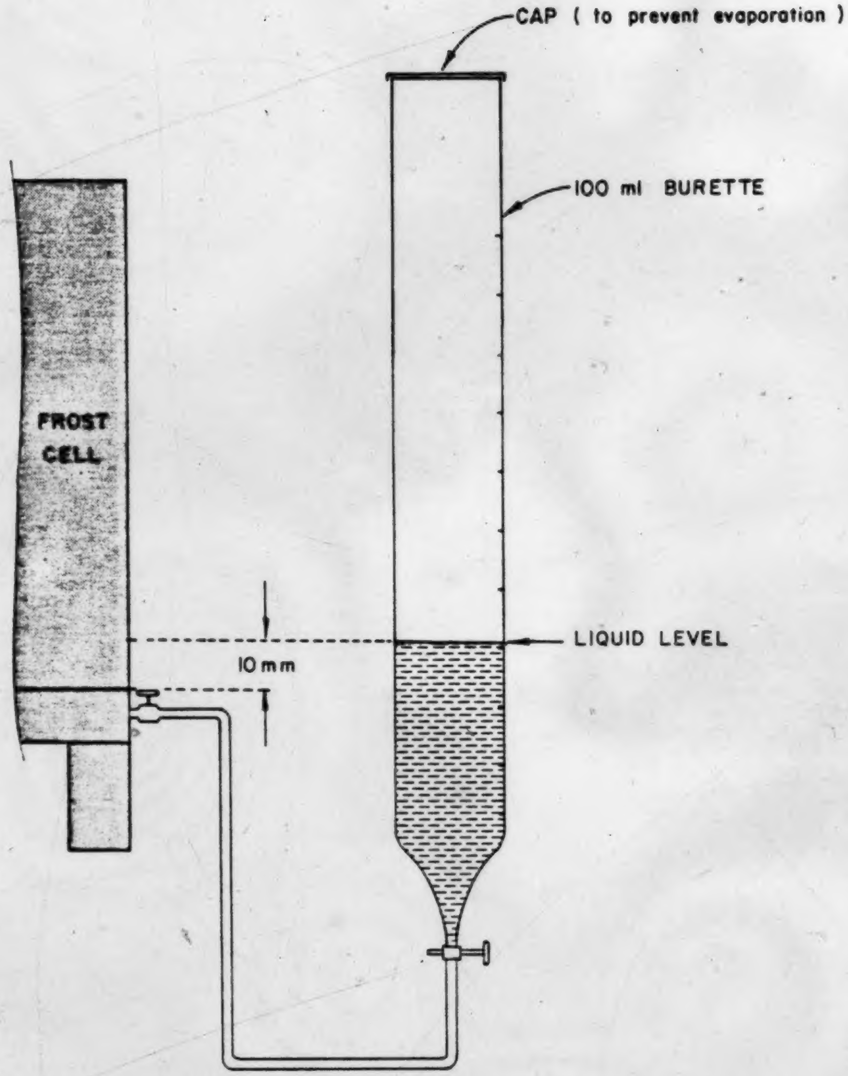

CAP (to prevent evaporation)
100 ml BURETTE
FROST CELL
LIQUID LEVEL
10 mm

FIGURE 3.6. SCHEMATIC DRAWING OF WATER-INTAKE MEASURING SYSTEM

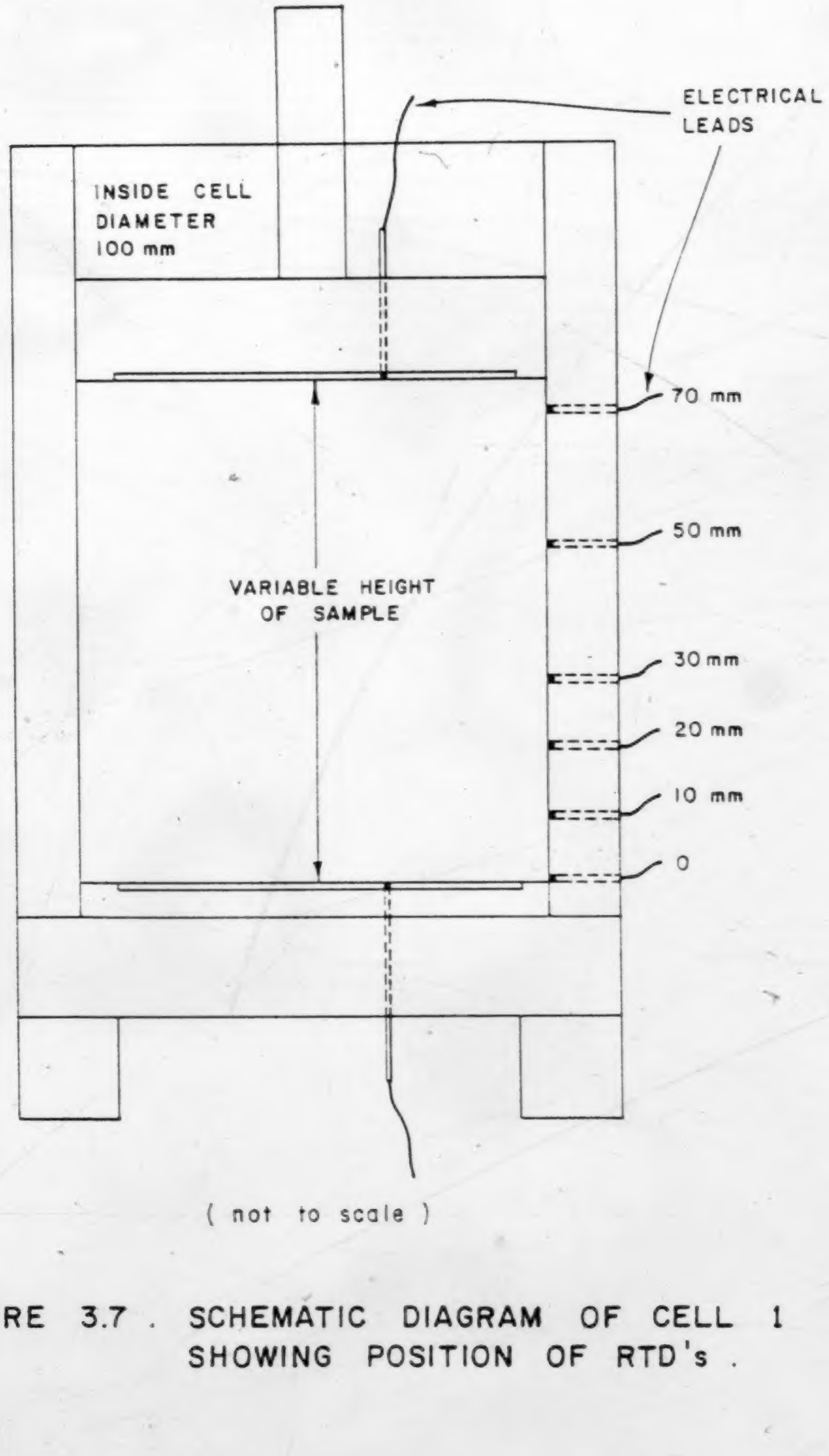

ELECTRICAL LEADS
INSIDE CELL DIAMETER 100 mm
70 mm
50 mm
VARIABLE HEIGHT OF SAMPLE
30 mm
20 mm
10 mm
0
(not to scale)

FIGURE 3.7 . SCHEMATIC DIAGRAM OF CELL 1 SHOWING POSITION OF RTD's .

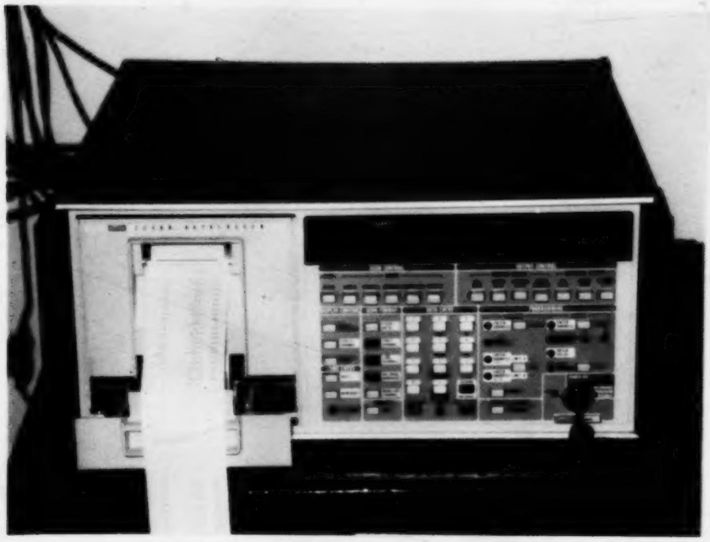


FIGURE 3.8 DATA ACQUISITION SYSTEM

system. The temperature for all devices could be monitored at any selected time interval. The information print-out in millivolts was applied to a calibration curve drawn from the manufacturer's specifications chart to obtain temperature readings. This straight line curve is shown in Figure A1 in Appendix A.

3.3 Sample Preparation and Description

All tests were conducted using municipal shredded waste obtained from the Strathcona shredder-transfer station located within the City of Edmonton. Samples were collected in February, August, September, and October for the four test series. Samples collected in August and September had a higher content of grass and tree trimmings than the February and October samples.

A description of sample preparation can best be described by the following steps:

a) Sample collection and preparation

Approximately 20 kg (wet mass basis) of shredded municipal refuse was collected from the shredding station for each series of tests conducted. This bulk sample was then hand-sorted to construct a final sample of about 2 kg which would closely approximate the characteristic weight components of municipal refuse as described in Section 2.4. Large non-porous objects such as glass and metals were removed from the sample and the remaining components were hand shredded so that the sample did not contain any portion larger than about 25 cm^2 in surface area. The sample was then mixed by hand to provide a thorough mixture of components. Figure 3.9 depicts typical samples used in the tests.

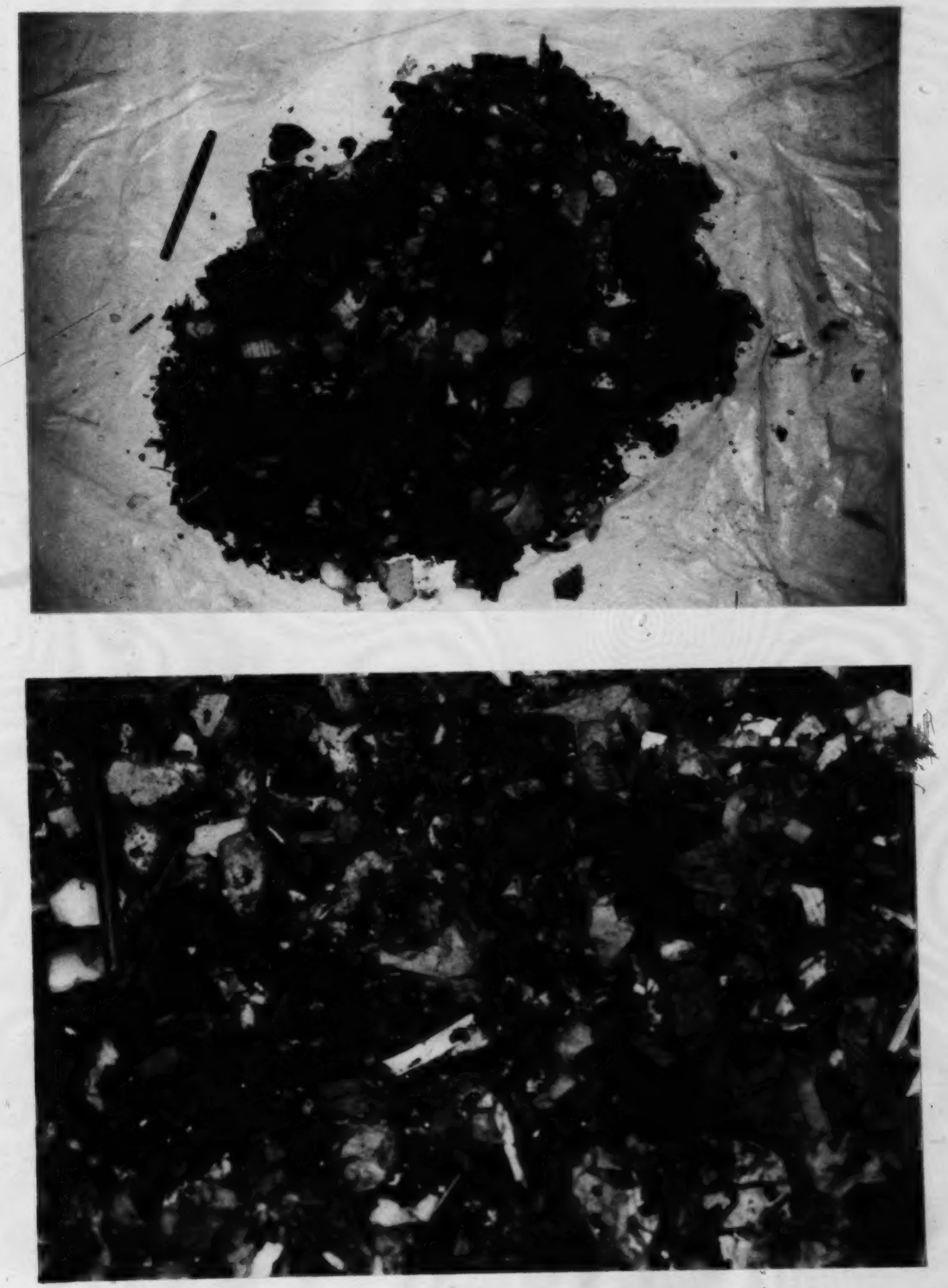


FIGURE 3.9 REFUSE SAMPLE MIXTURE

Table 3.1 provides a physical description of a prepared sample obtained in August. The various components were hand sorted and then weighed.

b) Sample Moisture Analysis

At the shredder station, the refuse is wetted at the base of the shredder. This is an operational procedure used to increase shredder efficiency and to suppress dust within the shredding station. A moisture content of 53% and 55% (wet mass basis) has been determined for this refuse (August and September, respectively).

For testing, the mixed sample was allowed to air dry in the laboratory to a desired moisture content. The moisture content analysis was performed on each cell sample. The average of four analyses for each cell sample was taken as the representative cell sample ~~moisture~~ content. The moisture content was conducted as described in Municipal Refuse Disposal, (APWA, 1966) and included in Appendix B.

c) Sample Volatile Solids Analysis

The dried sample portions from the moisture content analysis were used to obtain the volatile solids content for the prepared refuse samples. The average of four analyses for each cell sample was taken as the representative cell sample volatile solids content. Readings of 52%, 61%, 58% and 55% were obtained for February, August, September, and October samples, respectively. The volatile solids analysis procedure is described in Municipal Refuse Disposal and included in Appendix C.

TABLE 3.1

PHYSICAL COMPONENTS OF A PREPARED SAMPLE

Component	Approximate % of Sample (Wet Mass Basis)
Leaves/Grass	30
Paper	17
Plastics	14
Fines in a Pulverized Mixture	12
Tree Trimmings	9
Glass	6
Food Material	4
Stones/Ceramics	4
Wood	3
Rags	1
Total	100%

3.4 Sample Placement in Freeze Cells.

After the samples have been allowed to reach a desired moisture content they were double bagged in plastic garbage bags and stored over night in the cold room. This allowed the samples to cool and to permit a uniform moisture distribution.

The samples were weighed in the cold room as amounts were transferred into the freeze cells. The refuse was packed into the cells to a height which would correspond to a desired density range when the load cap was put into place. The load cap was under a pressure of 10 kPa which was created by the hangar-weight assembly.

The samples were allowed to consolidate for a one day period after which the height of the sample was determined and the density computed. Wet mass densities for the four test series varied from 377 kg/m^3 to 798 kg/m^3.

3.5 Test Procedure

All experiments were considered open system tests in that the samples were allowed access to a water supply (from the bottom) throughout the experiment.

The temperature control liquid circulation lines leading to the top and bottom of the freeze cells were connected and circulation commenced. The burettes were filled with water which was cooled in the cold room and the feed line allowed to drain to force out any contained air. The feed line was connected to the bottom of the cell and the water level was immediately brought up to the starting or reference level marked on the burette. Water intake commenced immediately. The top of the burette was covered to prevent evaporation.

Tests 1 to 6 were performed using circulating fluid temperatures of -11°C at the top of the sample and +4°C at the bottom. Tests 7 to 9 were not subjected to a temperature gradient for 18 days, after which temperatures of -11°C and +4°C were applied. Tests 10 to 12 were subjected to temperatures of -11°C and +8°C. For each sample therefore, a temperature gradient through the frozen fringe was calculated.

A pressure of 10 kPa was applied to the load cap for all tests to maintain a desired sample density. The position of the load cap was measured daily throughout the test to determine if movement was occurring.

Water uptake was observed and recorded a number of times each day during the initial 3-5 days of testing, after which daily readings were conducted.

Upon completion of the tests, the freeze cells were disassembled and samples were cut into sections of approximately 20 mm thickness for moisture content analysis. Photographs were taken of the sample columns and are shown in Figures 3.10 to 3.14. Figure 3.11 shows the presence of ice in the voids within the frozen zone. Figure 3.12 shows a section of the sample column taken for moisture analysis. Figure 3.13 shows the uppermost section of the sample with ice filling the void spaces.

Table 3.2 is a summary of test information.

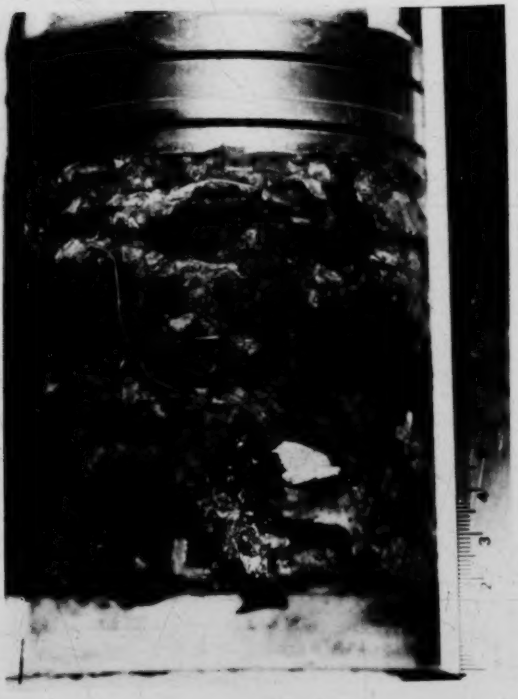
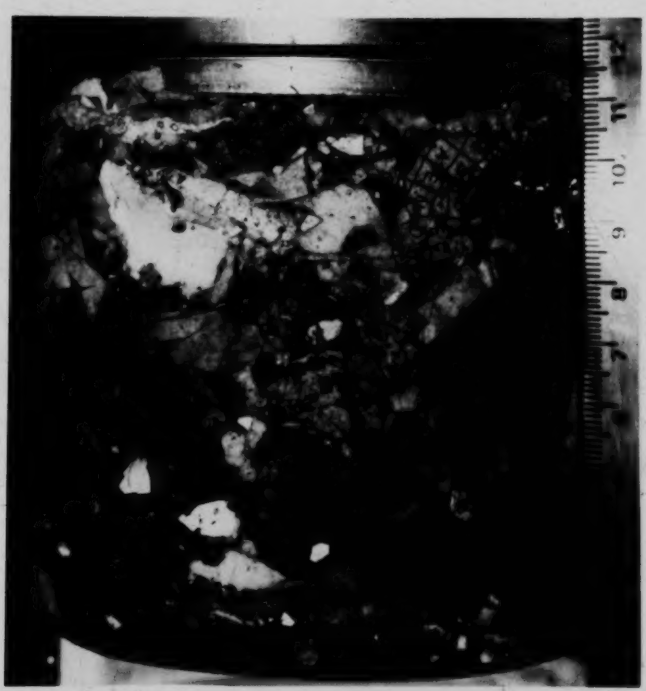


FIGURE 3.10 SAMPLE COLUMN AT TEST END

FIGURE 3.11 ICE CRYSTALS FILLING VOID SPACES



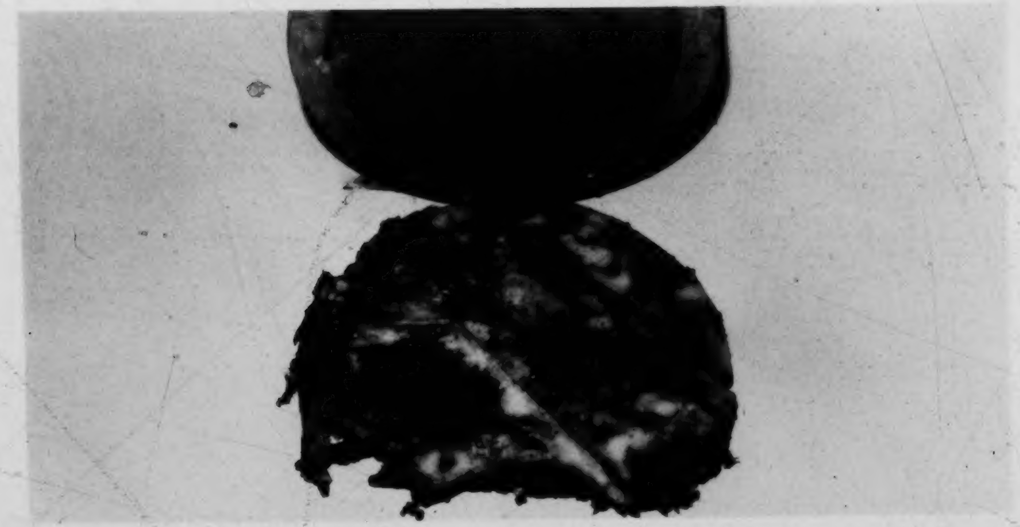


FIGURE 3.12 TOP SECTION OF SAMPLE FOR MOISTURE ANALYSIS

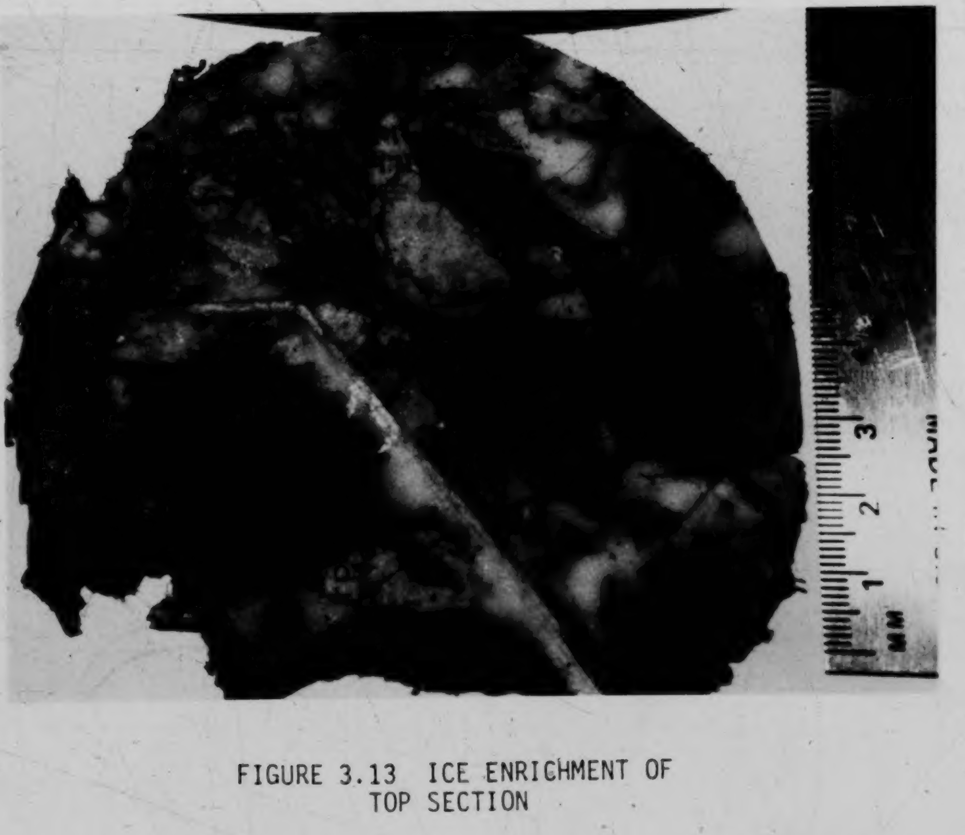


FIGURE 3.13 ICE ENRICHMENT OF TOP SECTION

TABLE 3.2

SUMMARY OF TESTS

Test No	Temperatures [Top, Bottom](°C)	Length of Test (Days)	Sample Mass (g, wet mass)	Cell Volume ($10^{-4}m^3$)	Wet Density (kg/m^3)	Overburden Pressure (kPa)
1	-11, +4	21	537	6.72	798	10
2	-11, +4	21	628	8.85	710	10
3	-11, +4	21	626	9.20	680	10
4	-11, +4	21	403	6.44	626	10
5	-11, +4	21	618	9.79	631	10
6	-11, +4	21	454	8.65	525	10
7	After 18d, -11, +4	36	303	6.41	472	10
8	After 18d, -11, +4	36	540	9.23	585	10
9	After 18d, -11, +4	36	596	9.23	646	10
10	-11, +8	37	562	7.46	753	10
11	-11, +8	37	416	9.03	460	10
12	-11, +8	37	355	9.42	377	10

4. EXPERIMENTAL RESULTS

4.1 Introduction

Data from each experiment includes the temperature at various points in the sample, cumulative water intake with time, initial moisture content, and the final moisture content of sample sections. All data are presented in graphical form in Figures 4.1 to 4.12, the Moisture Distribution Graphs. The temperature profile curve connects data points obtained at the intervals where the RTD's are placed into the cell wall. The final moisture content curve connects data points which represent the moisture content of a section of sample and plotted at the midrange point for that section. For example, if a moisture content of 40% was obtained for the 0-20 mm bottom sample section, then the data point was plotted at the 10 mm interval. A summary of water intake rates and pertinent details of each test is given in Table 4.1.

4.2 Results

The experimental results for cumulative water intake are shown in graphic form in Figures 4.13 to 4.25.

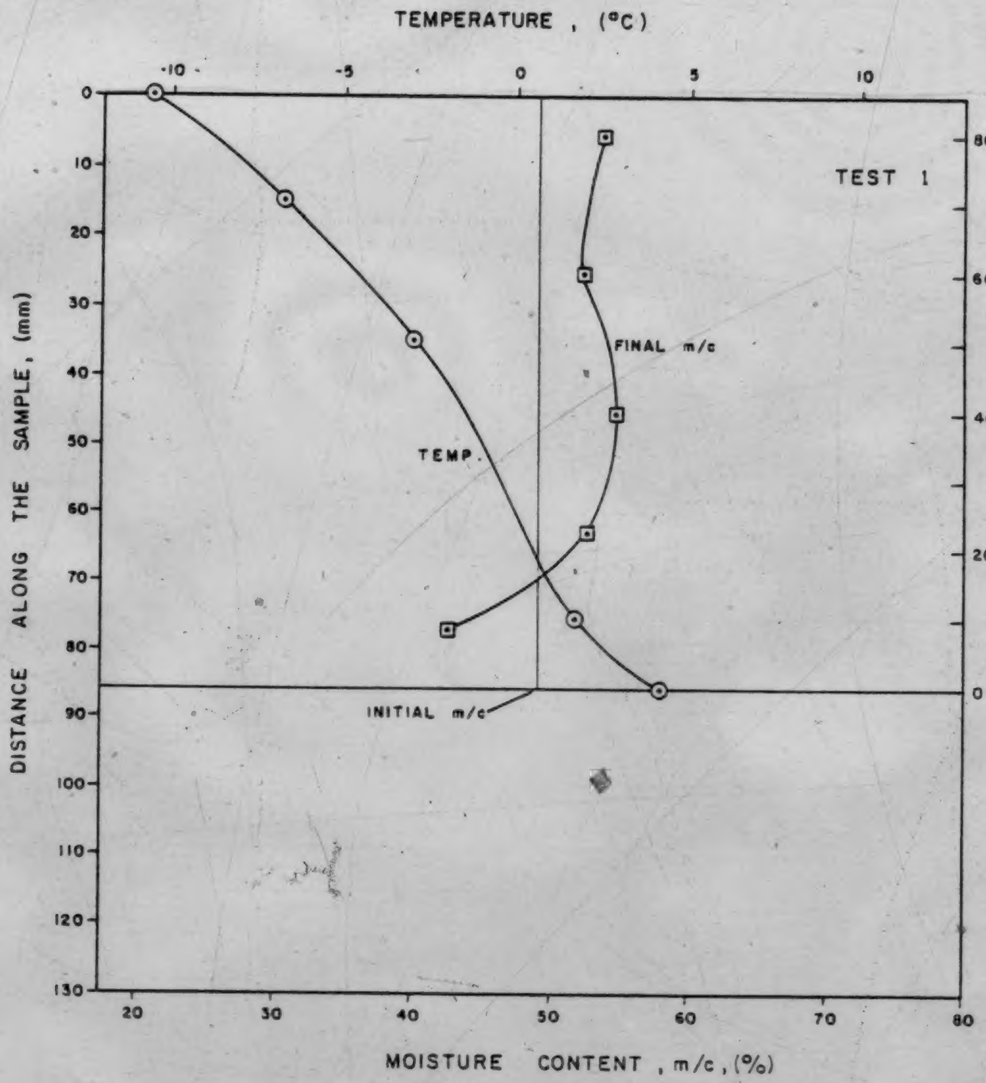
With the exception of tests 1 and 12 (Figures 4.14 and 4.25, respectively) the data is shown in three curves for each test. The three curves represent measured cumulative water uptake, capillary cumulative water uptake, and temperature induced cumulative uptake, as indicated for each test.

Figure 4.13 shows the capillarity curve for solid waste and represents the capillary cumulative water uptake as measured for the first 18 days with no temperature gradient applied to tests 7, 8, and 9. The logarithmic function, log V = log a - n log (t+1) was then applied to the average curve from the three capillary test curves. By plotting the data, a value of 8.6 ml was defined for "a" intercept and a value of 0.56 was defined for the "n" slope.

The logarithmic relationship reduces to $V = a(t+1)^n$, from which the capillarity curve for solid waste was plotted as shown in Figure 4.13. This curve was then plotted with the measured water uptake curve in Figures 4.14 to 4.25. The difference between the measured water uptake curve and the capillary water uptake curve yielded a third curve - temperature induced water uptake, i.e., omitting the effects of capillarity in data analysis. A "best-fit" straight line drawn through this curve defines the water intake rate attributed to the freezing process. This value is considered in data interpretation and is shwon along with other test results in Table 4.1. Tests 1 and 12 did not show a water intake value since the measured uptake did not exceed the values attributed to capillary action as defined by the capillary curve.

Temperature and moisture distribution curves for each experiment are shown in the Moisture Distribution Graphs, Figures 4.1 to 4.12. This information was used in calculating the temperature gradient and moisture content of the frozen fringe.

Visual observations of samples at the end of the test indicated that the bottom of the sample was wet to a height of 10 mm to 20 mm. This flooding of the sample base insured a water supply for moisture uptake and migration through the samples. The sample columns generally showed saturation or wet conditions at the bottom 10-20 mm followed by a drier zone up to the frost front which varied in location for individual test columns. The zone below the frost front appeared darker due to the



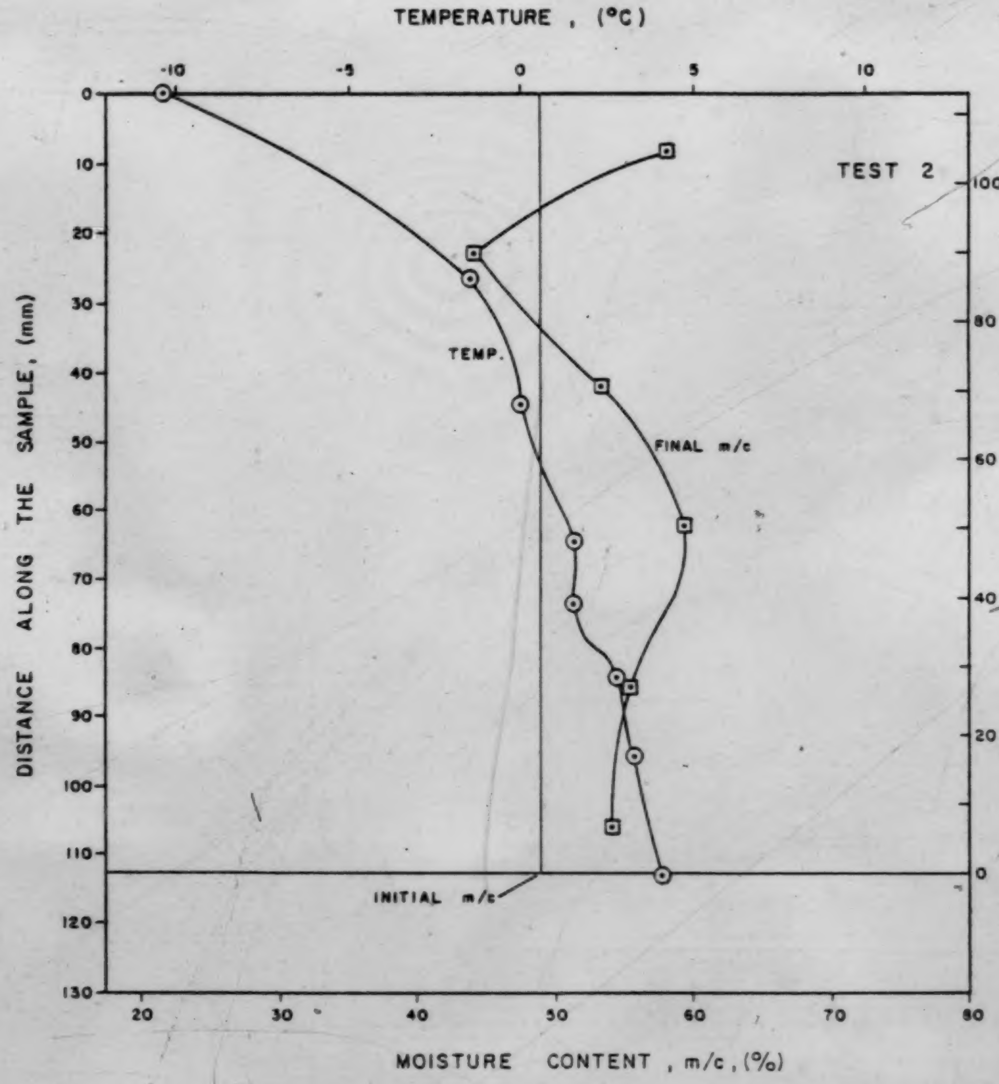
TIME Δt = 22 d

WET DENSITY = 798 kg/m^3

INITIAL m/c = 49 %

WATER UPTAKE = 32.3 ml

FIGURE 4.1 MOISTURE DISTRIBUTION GRAPH



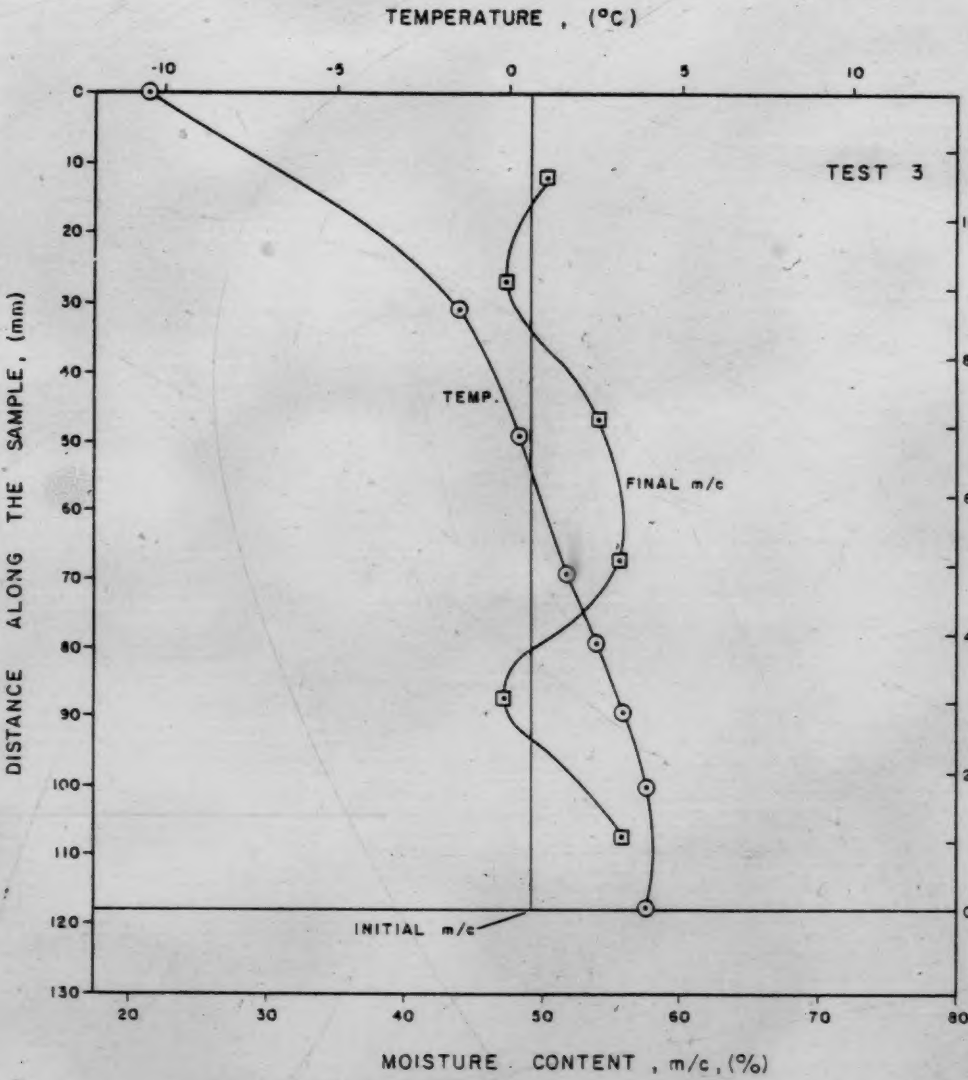
TIME Δ t = 22 d

WET DENSITY = 710 kg/m^3

INITIAL m/c = 49 %

WATER UPTAKE = 92.0 ml

FIGURE 4.2 MOISTURE DISTRIBUTION GRAPH



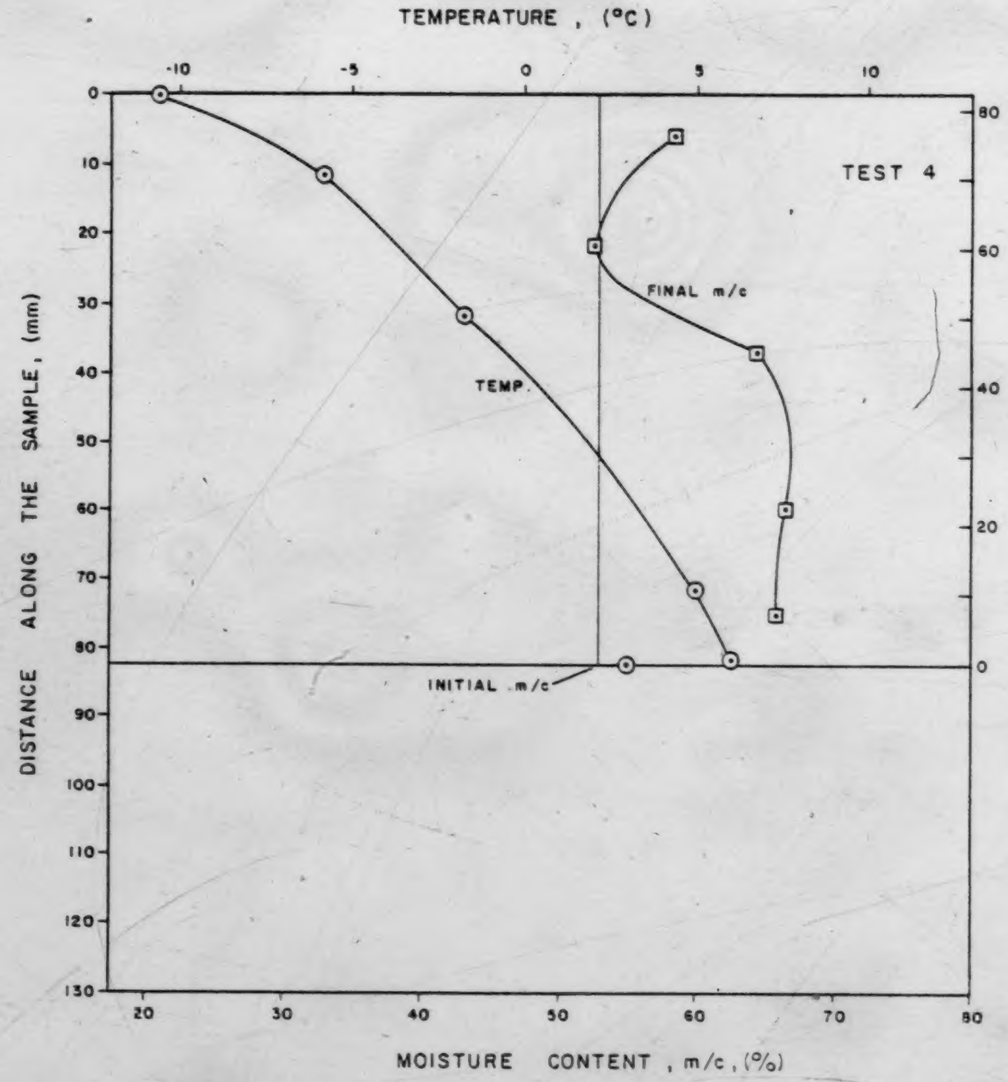
TIME Δ t = 22 d

WET DENSITY = 680 kg/m^3

INITIAL m/c = 49 %

WATER UPTAKE = 57.0 ml

FIGURE 4.3 MOISTURE DISTRIBUTION GRAPH



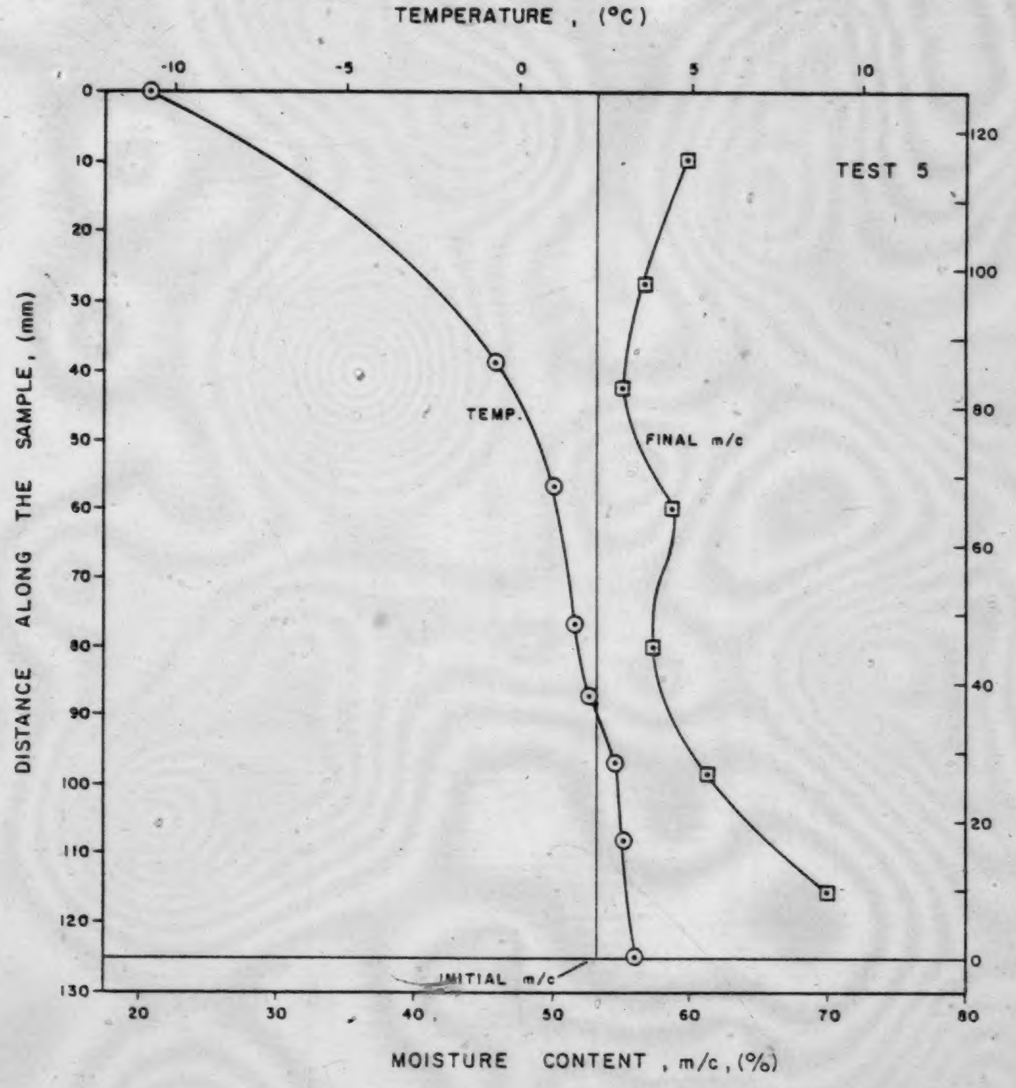
TIME Δt = 21 d

WET DENSITY = 626 kg/m^3

INITIAL m/c = 53 %

WATER UPTAKE = 137.0 ml

FIGURE 4.4 MOISTURE DISTRIBUTION GRAPH



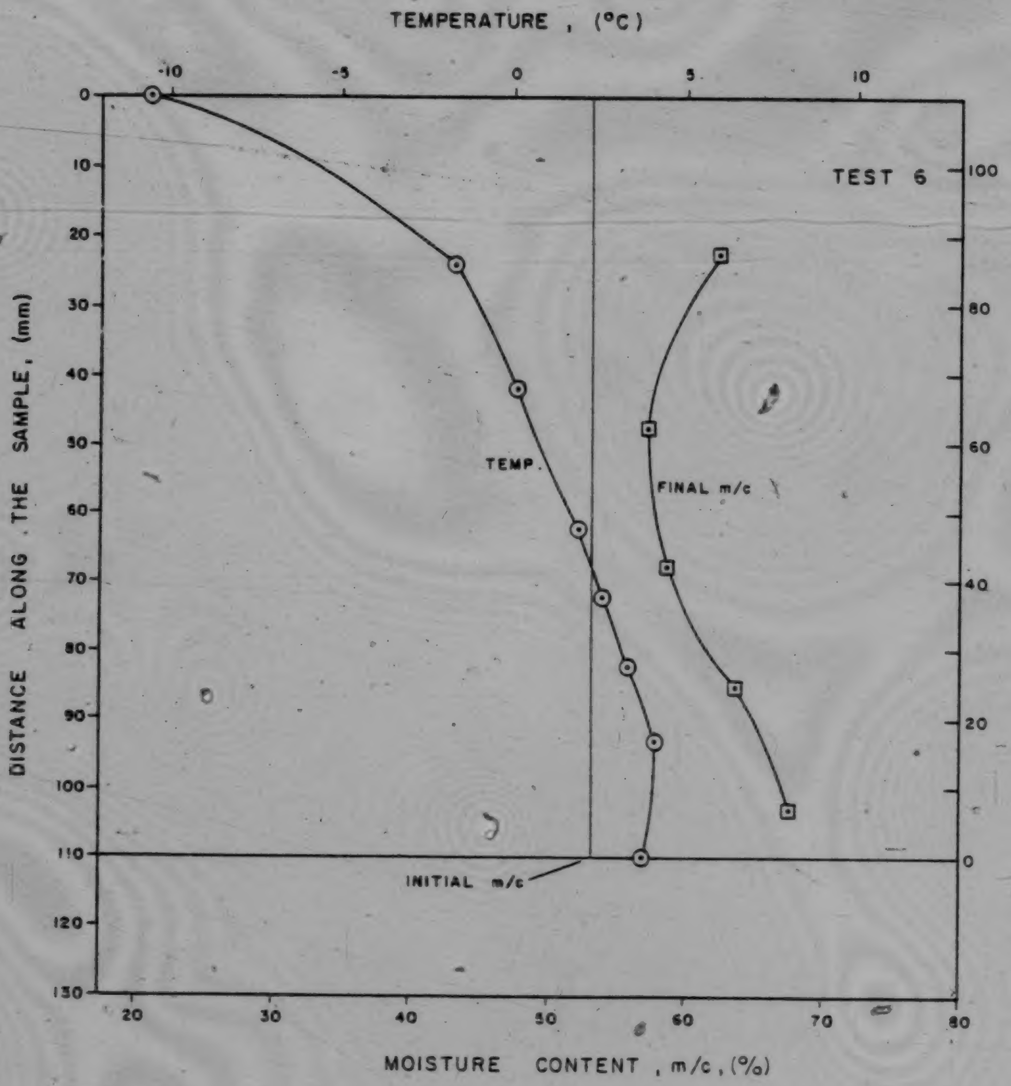
TIME Δ t = 21 d

WET DENSITY = 631 kg/m^3

INITIAL m/c = 53 %

WATER UPTAKE = 89.5 ml

FIGURE 4.5 MOISTURE DISTRIBUTION GRAPH



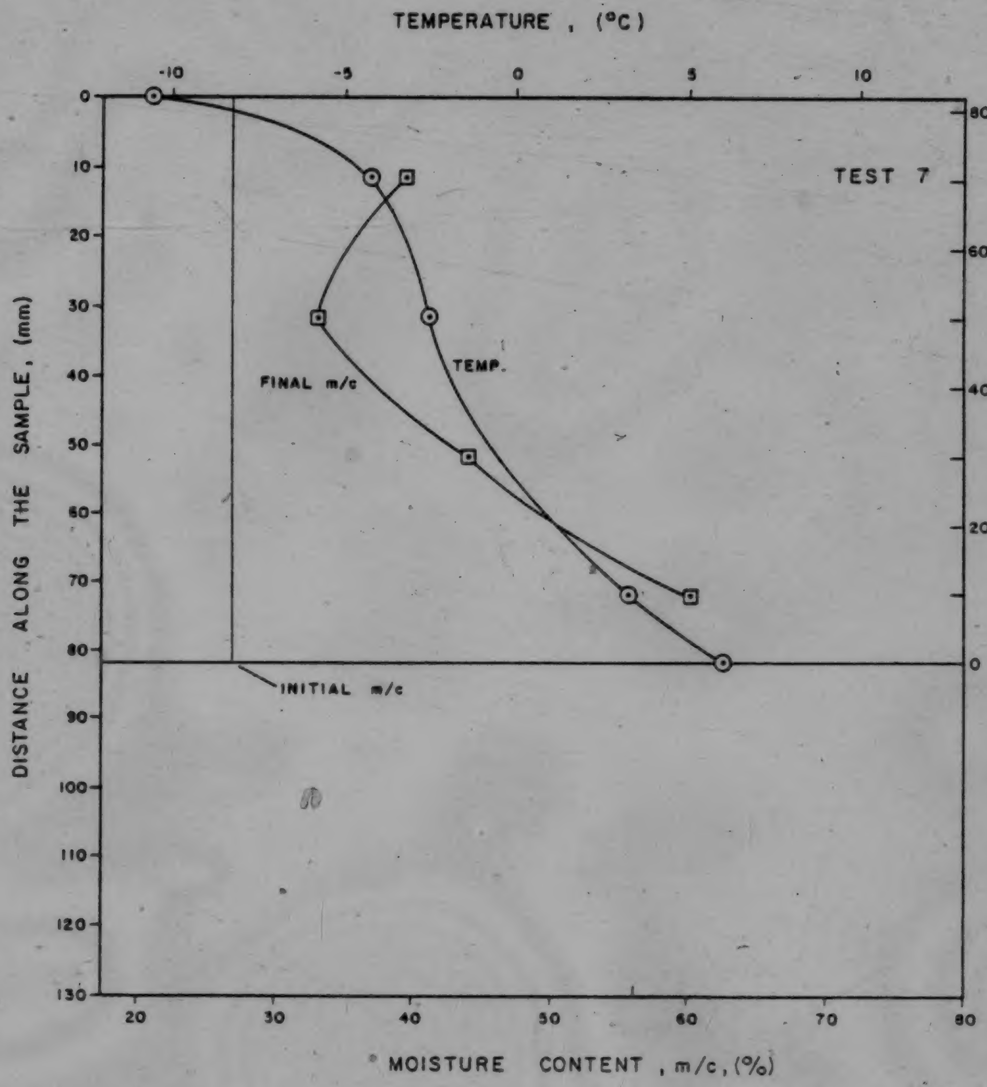
TIME Δt = 21 d

WET DENSITY = 525 kg/m^3

INITIAL m/c = 53 %

WATER UPTAKE = 77.2 ml

FIGURE 4.6 MOISTURE DISTRIBUTION GRAPH



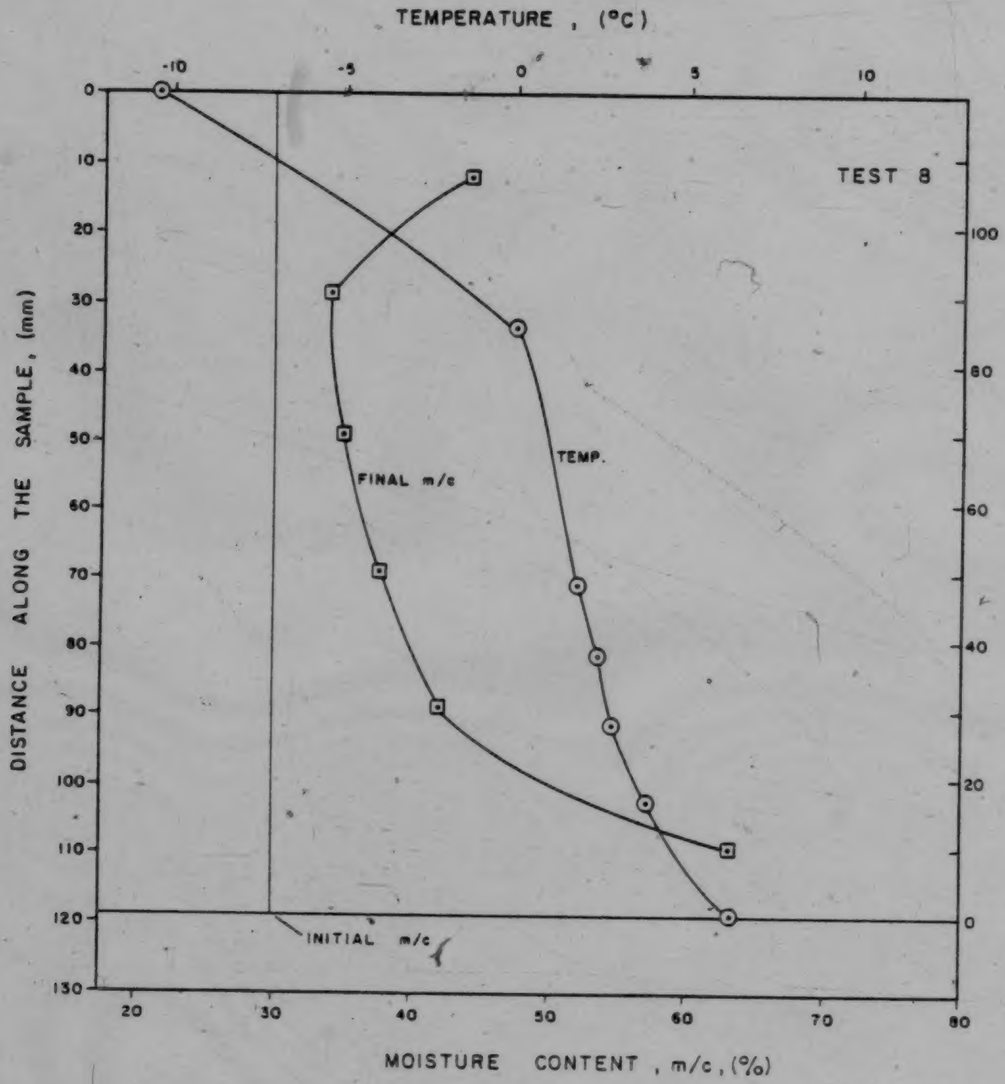
TIME Δ t = 36 d

WET DENSITY = 472 kg/m^3

INITIAL m/c = 27 %

WATER UPTAKE = 89 ml

FIGURE 4.7 MOISTURE DISTRIBUTION GRAPH



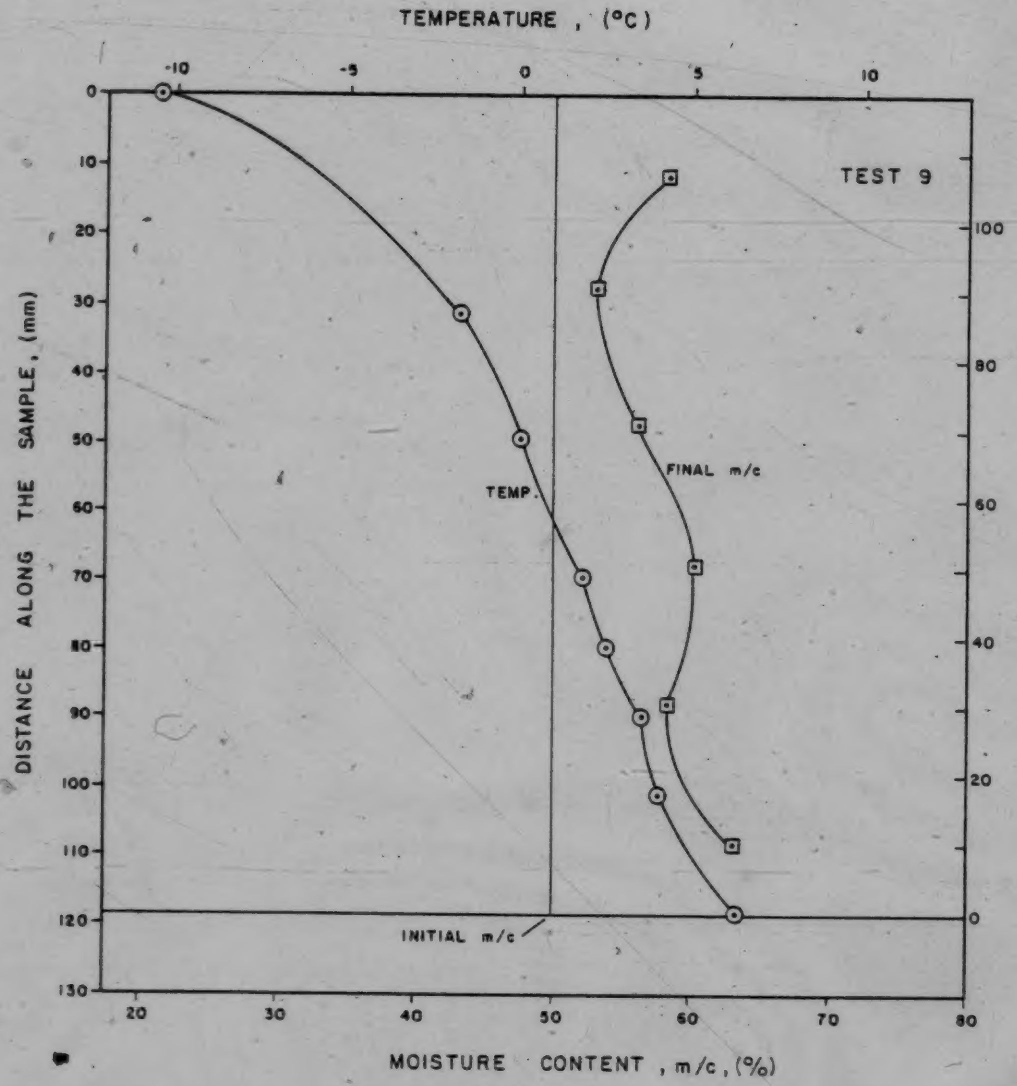
TIME Δ t = 36 d

WET DENSITY = 585 kg/m³

INITIAL m/c = 30 %

WATER UPTAKE = 79 ml

FIGURE 4.8 MOISTURE DISTRIBUTION GRAPH



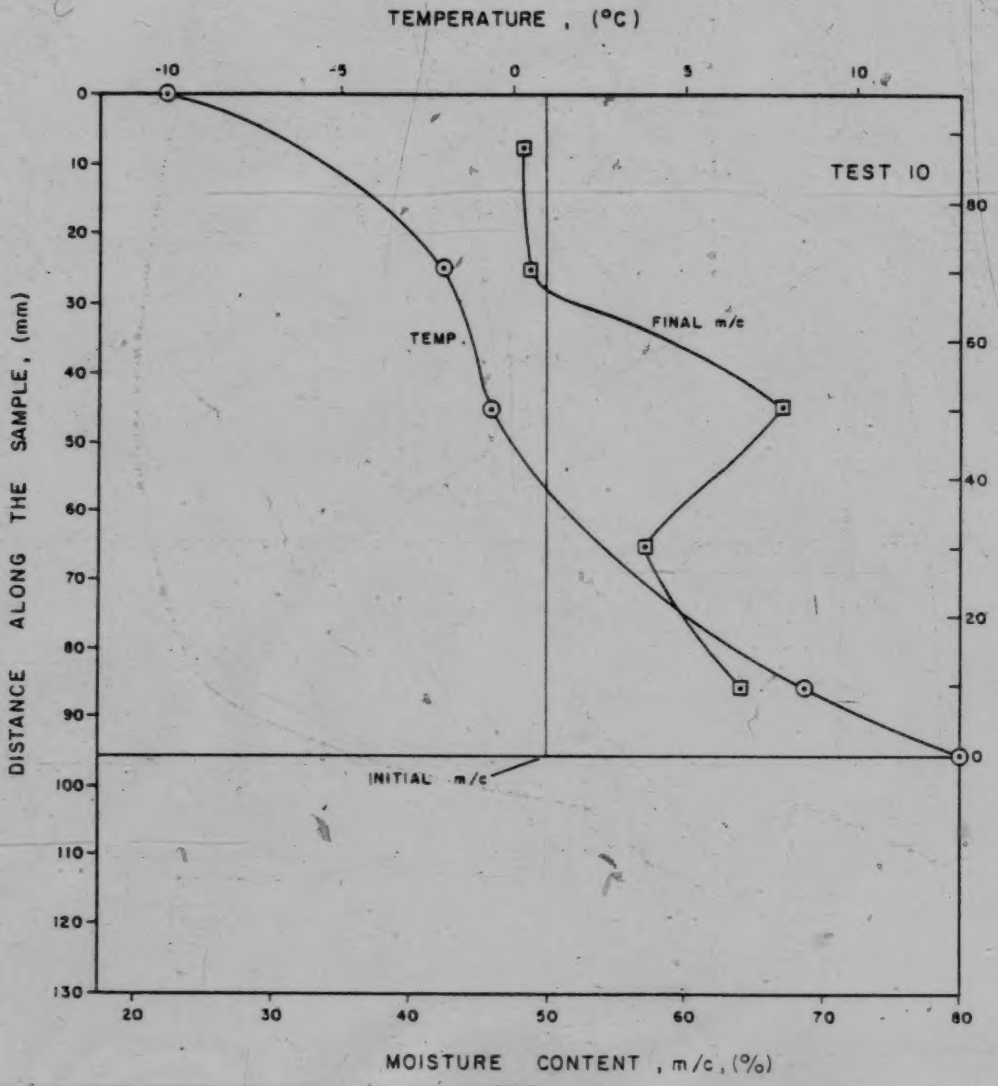
TIME Δ t = 36 d

WET DENSITY = 646 kg/m^3

INITIAL m/c = 50 %

WATER UPTAKE = 101 ml

FIGURE 4.9 MOISTURE DISTRIBUTION GRAPH



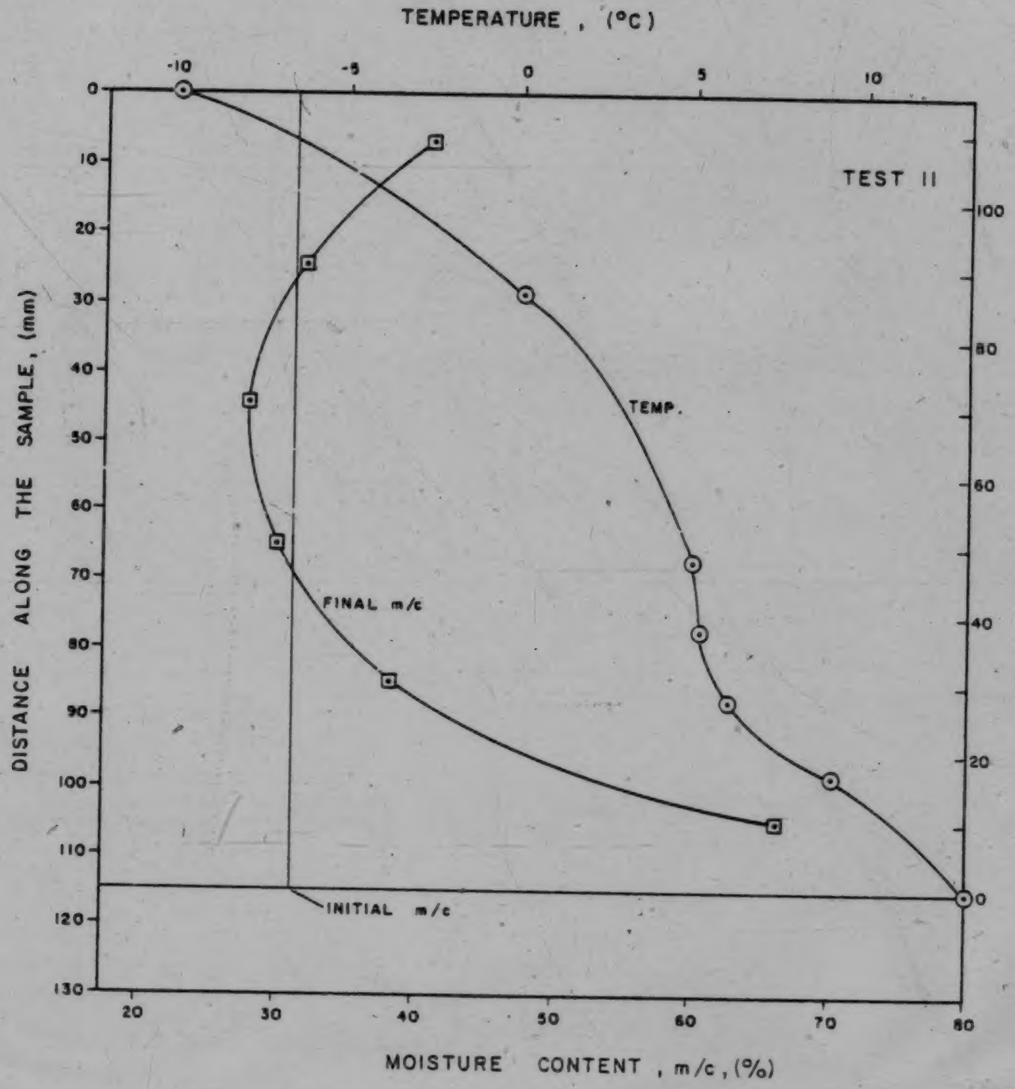
TIME Δ t = 37 d

WET DENSITY = 753 kg/m^3

INITIAL m/c = 50 %

WATER UPTAKE = 108 ml

FIGURE 4.10 MOISTURE DISTRIBUTION GRAPH



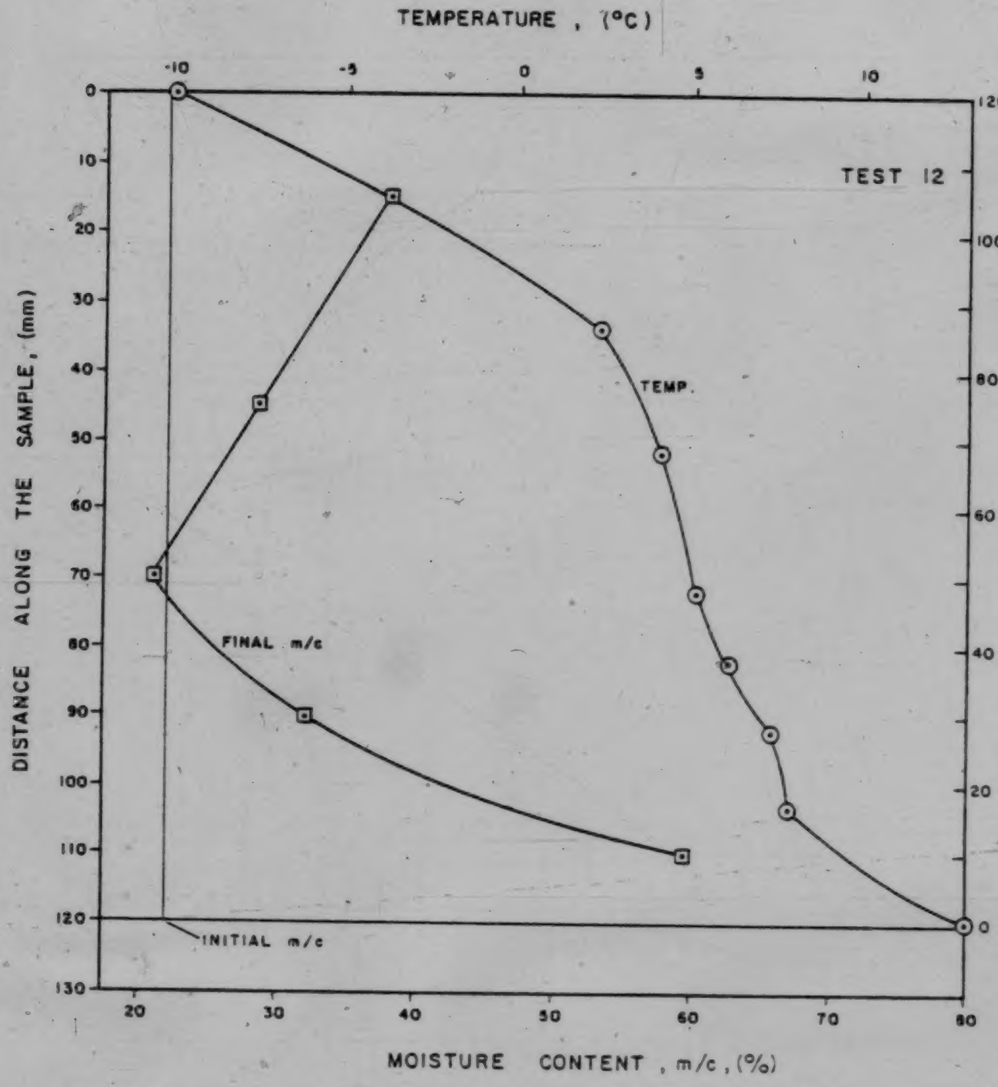
TIME Δ t = 37 d

WET DENSITY = 460 kg/m^3

INITIAL m/c = 31 %

WATER UPTAKE = 96 ml

FIGURE 4.11 MOISTURE DISTRIBUTION GRAPH



TIME Δt = 37 d

WET DENSITY = 377 kg/m^3

INITIAL m/c = 22 %

WATER UPTAKE = 46 ml

FIGURE 4.12 MOISTURE DISTRIBUTION GRAPH

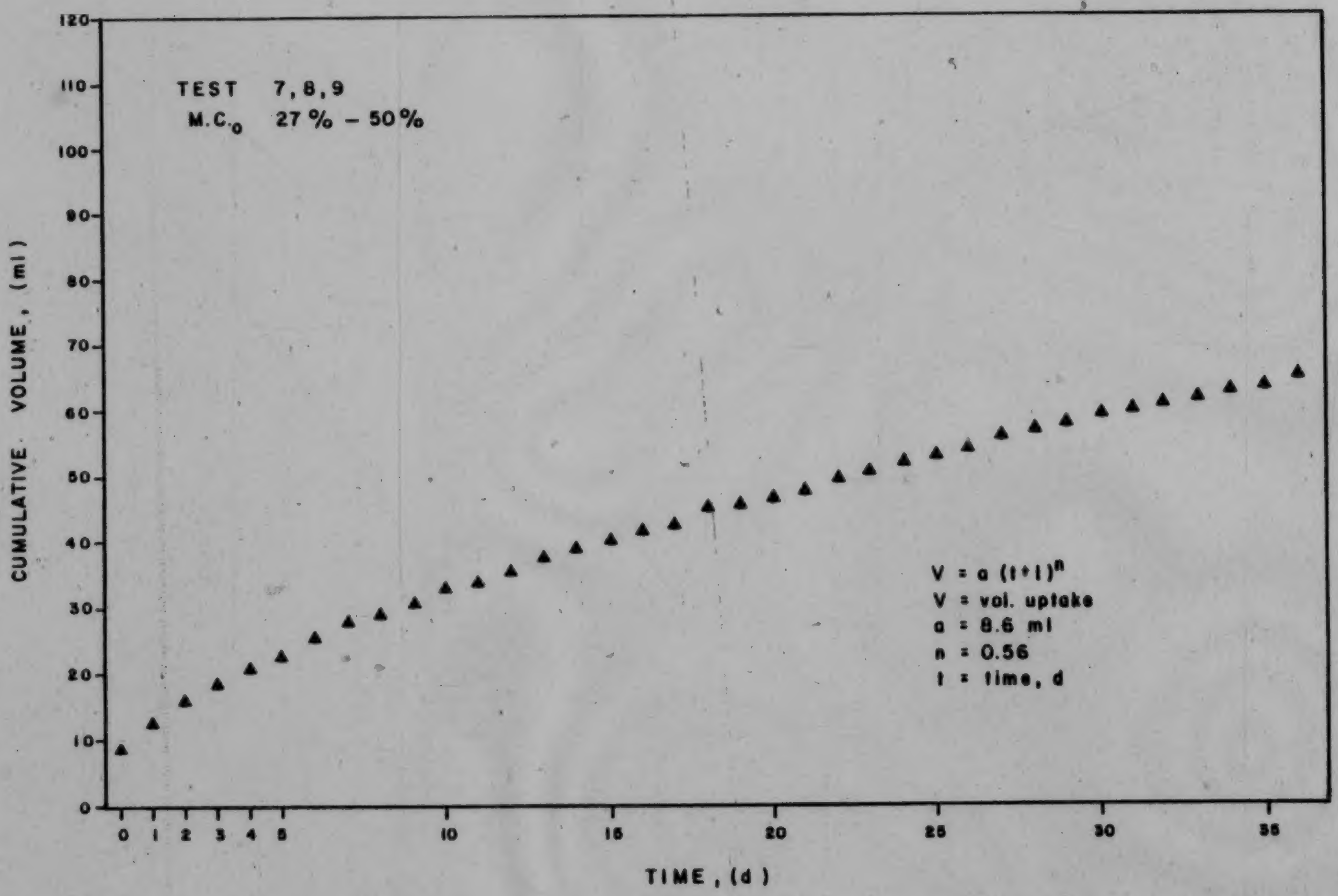


FIGURE 4.13 CAPILLARITY CURVE FOR SOLID WASTE

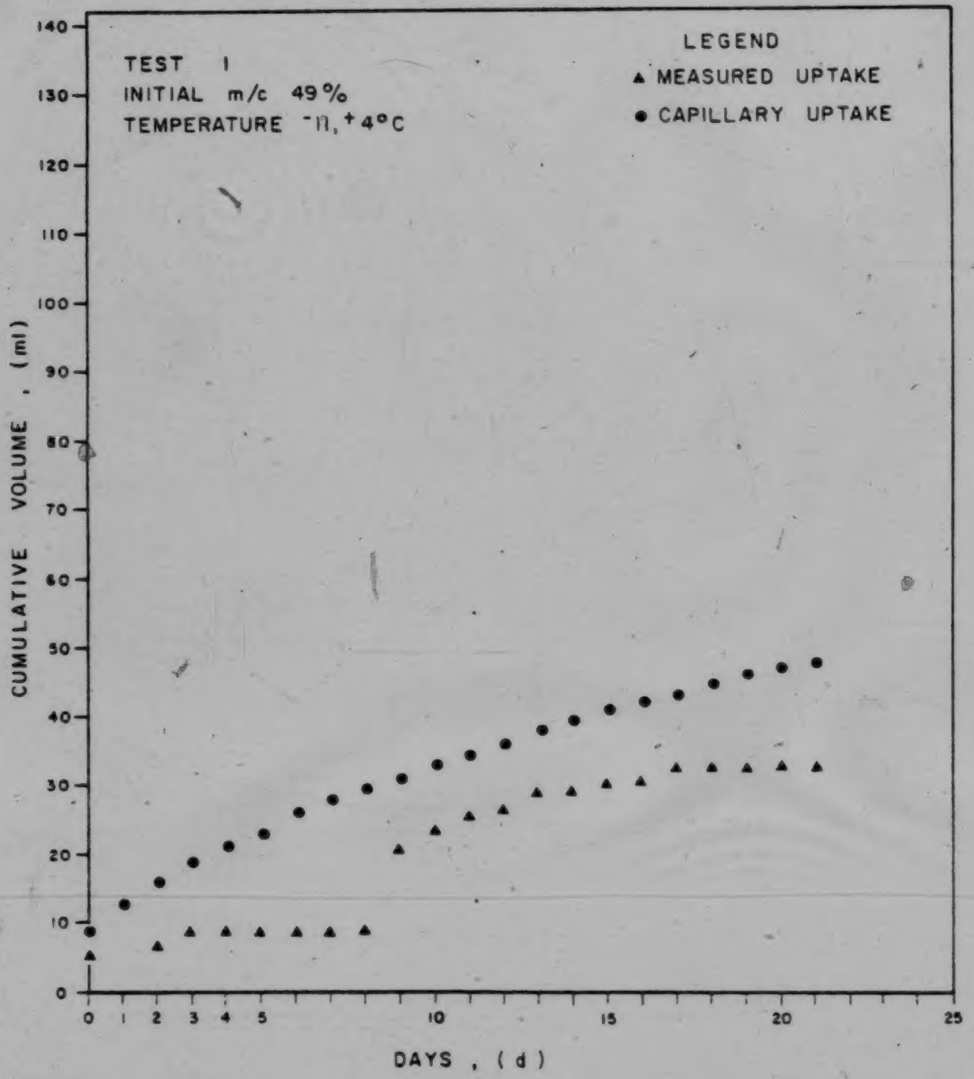


FIGURE 4.14 WATER UPTAKE

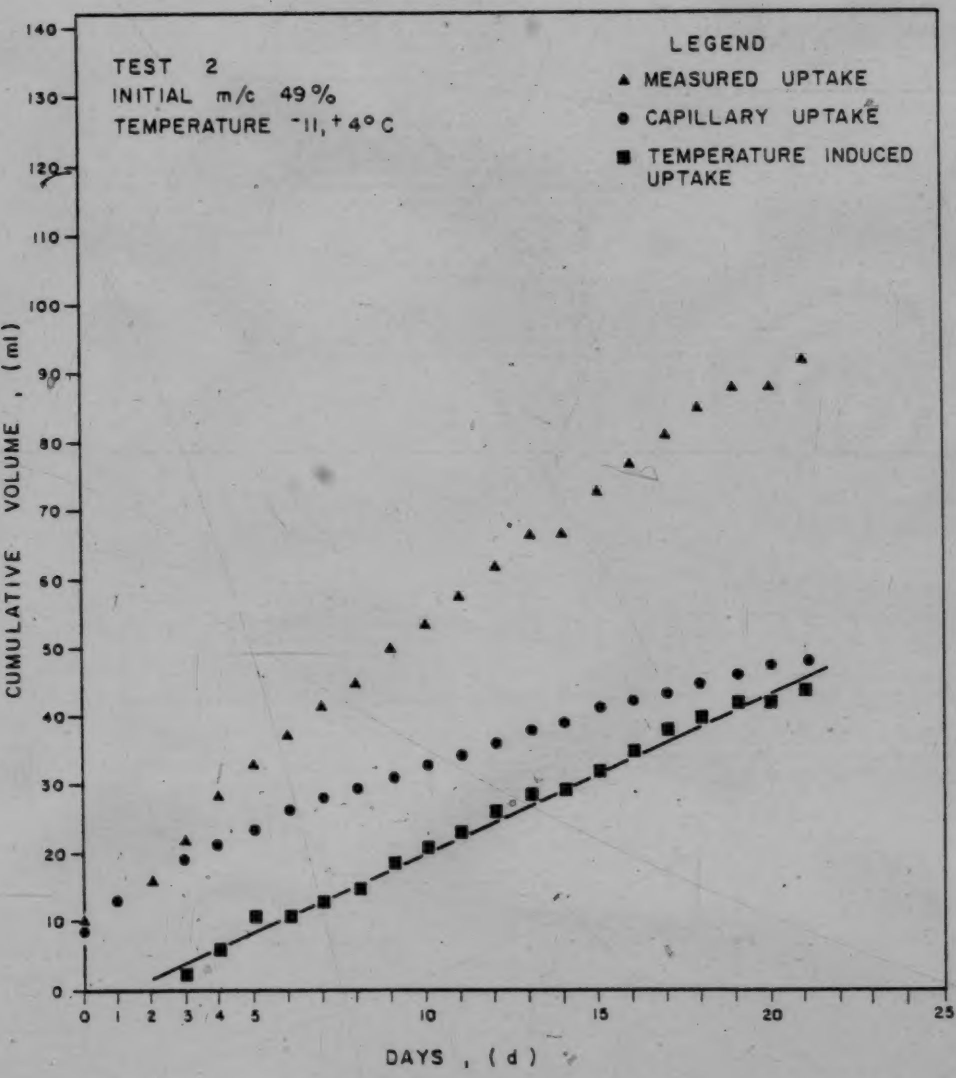


FIGURE 4.15 WATER UPTAKE

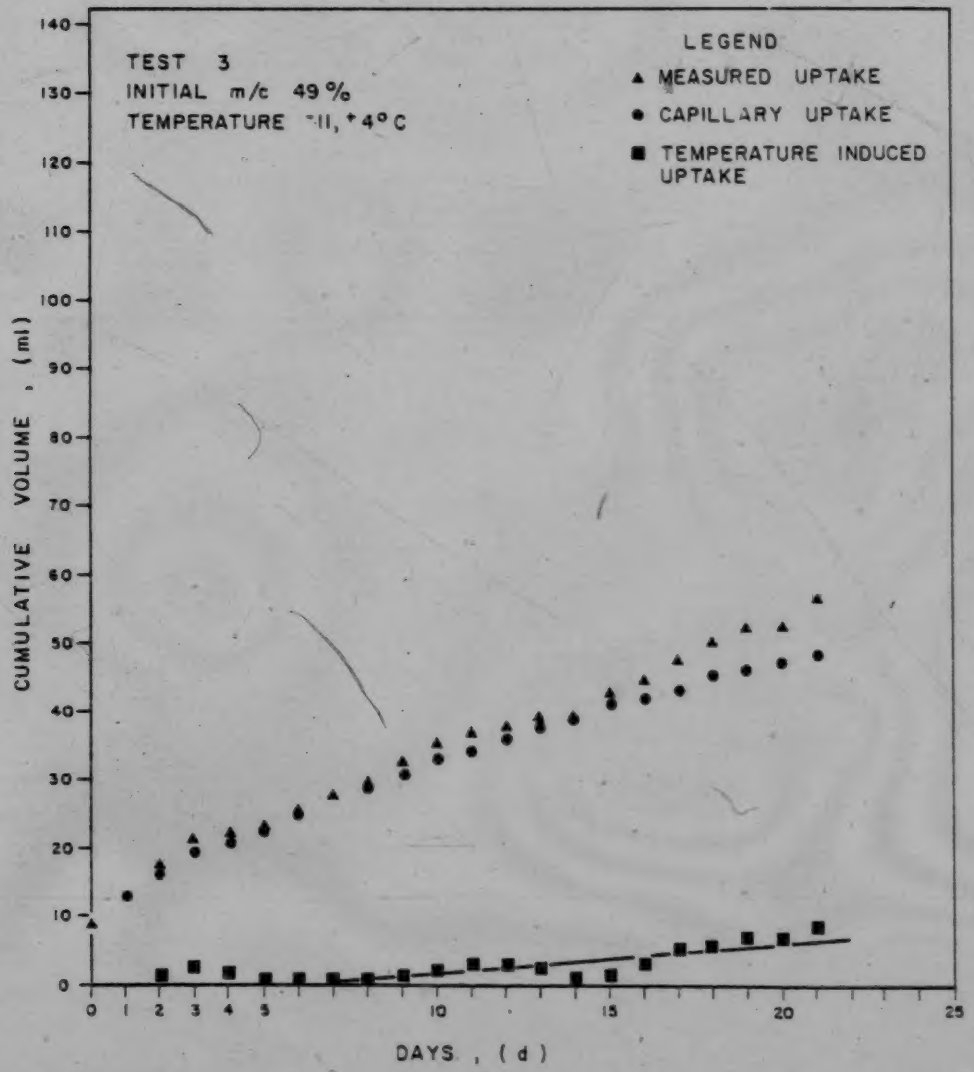


FIGURE 4.16 WATER UPTAKE

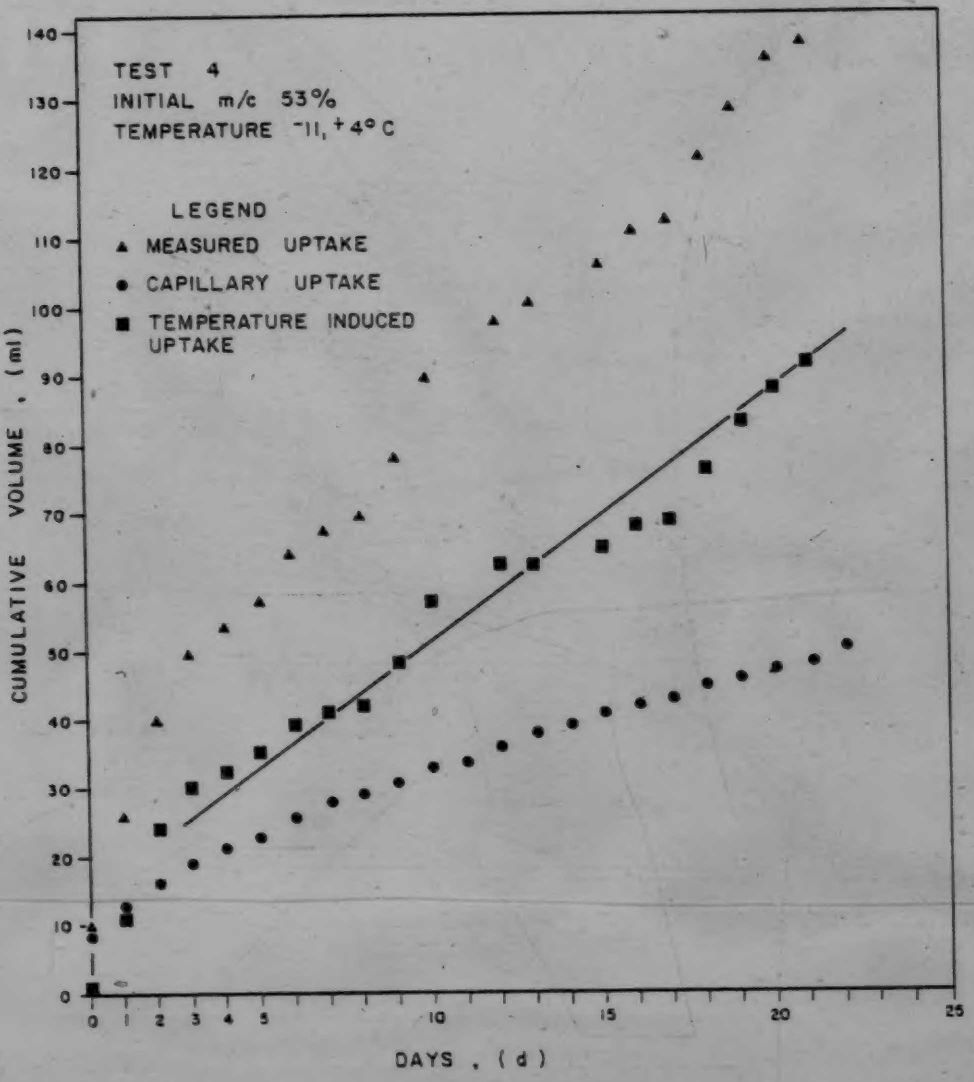


FIGURE 4.17 WATER UPTAKE

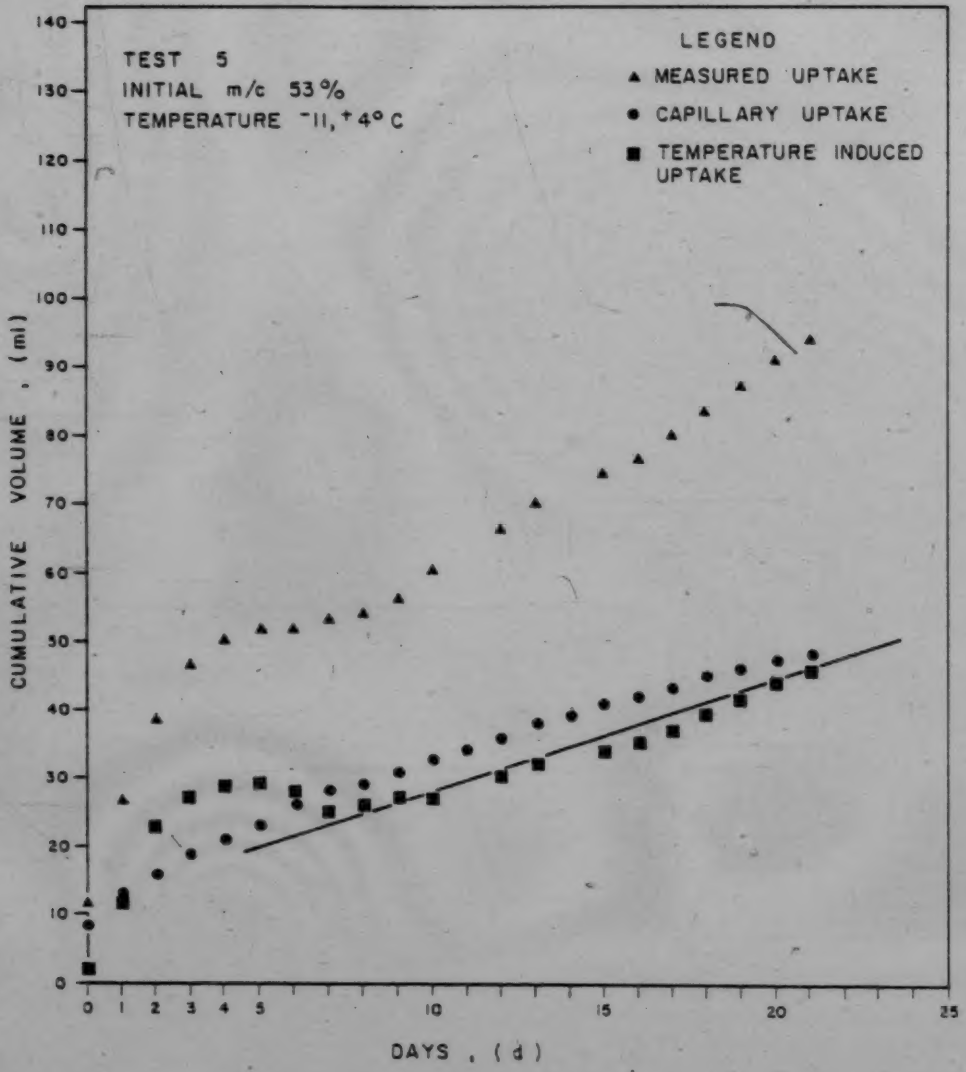


FIGURE 4.18 WATER UPTAKE

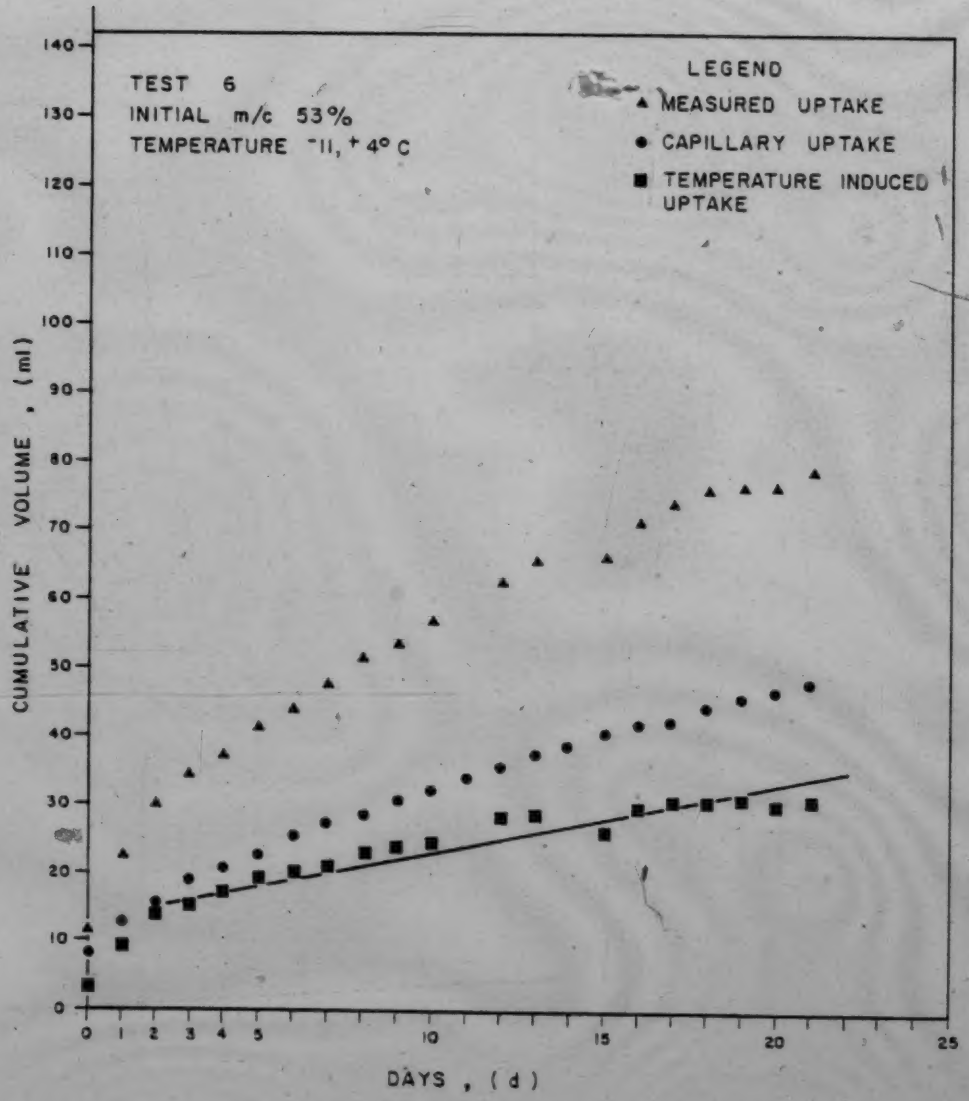


FIGURE 4.19 WATER UPTAKE

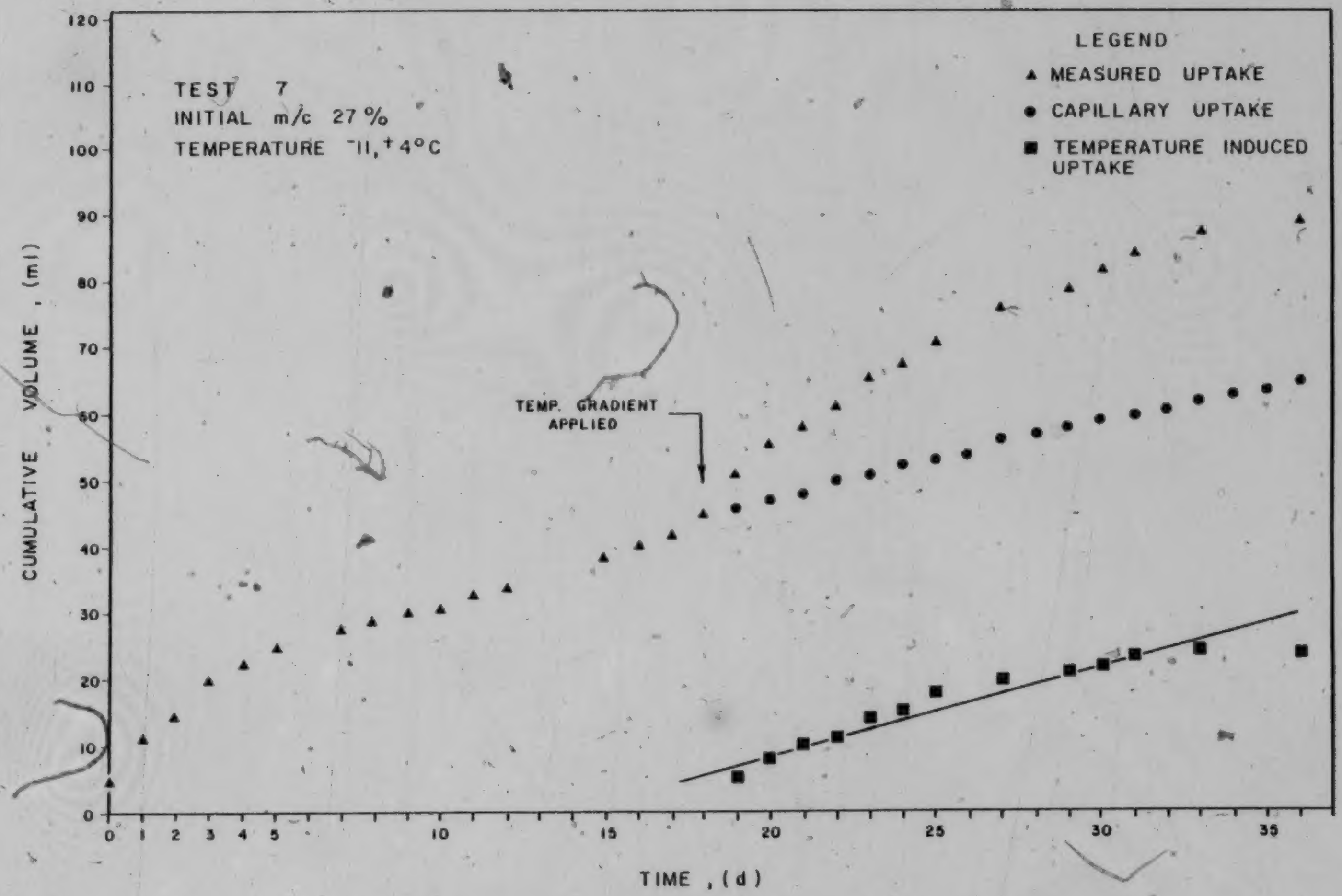


FIGURE 4.20 WATER UPTAKE

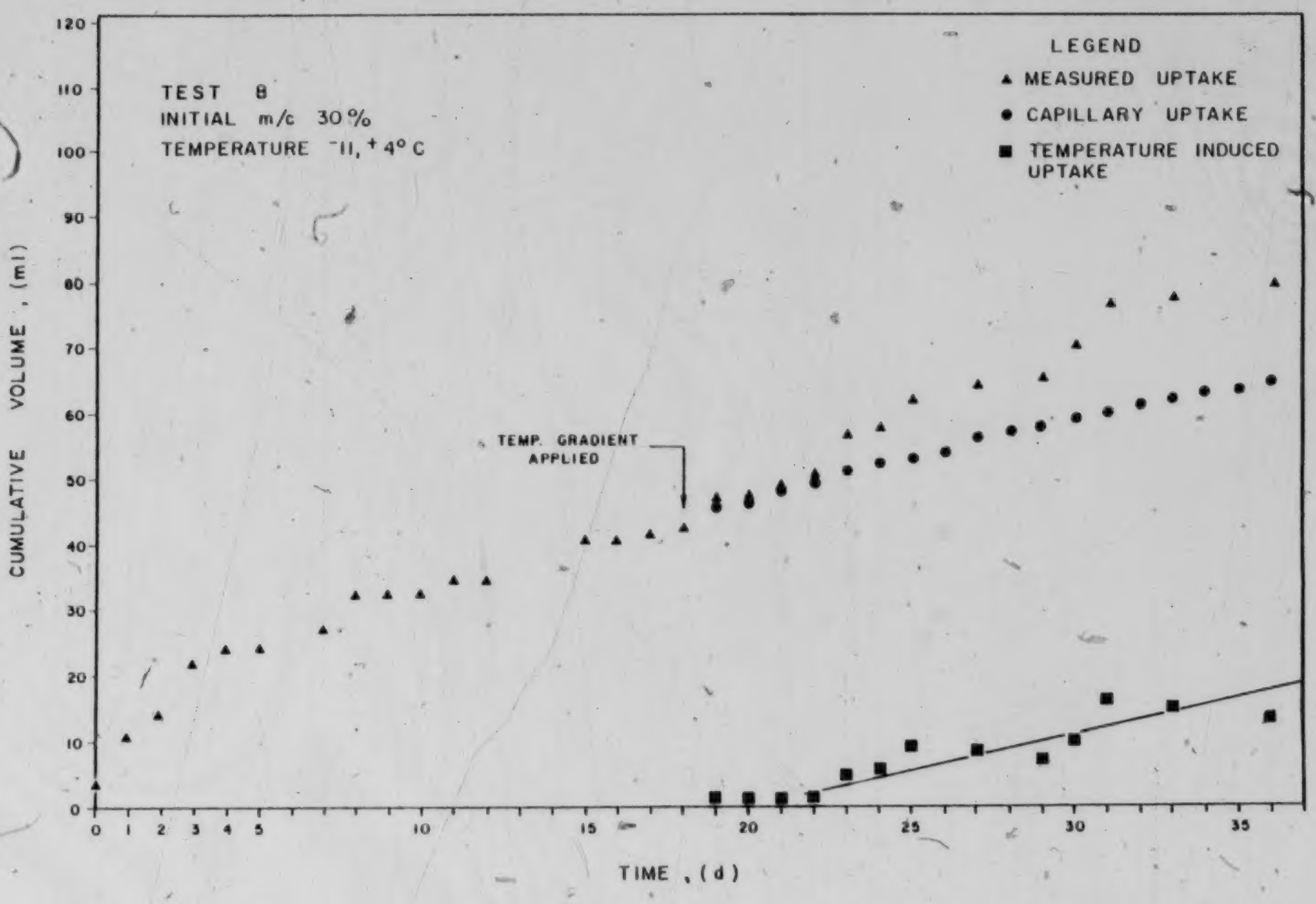


FIGURE 4.21 WATER UPTAKE

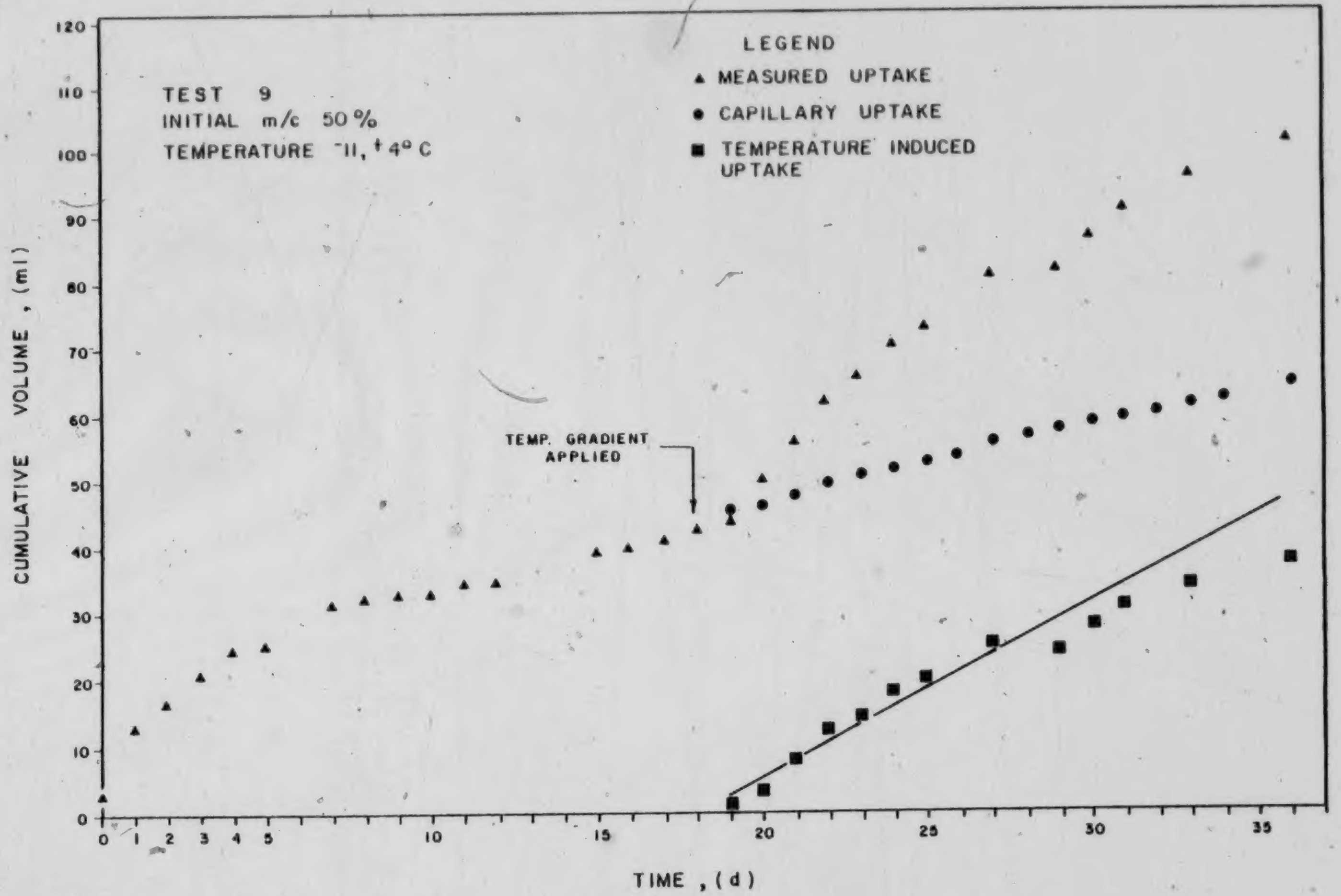


FIGURE 4.22 WATER UPTAKE

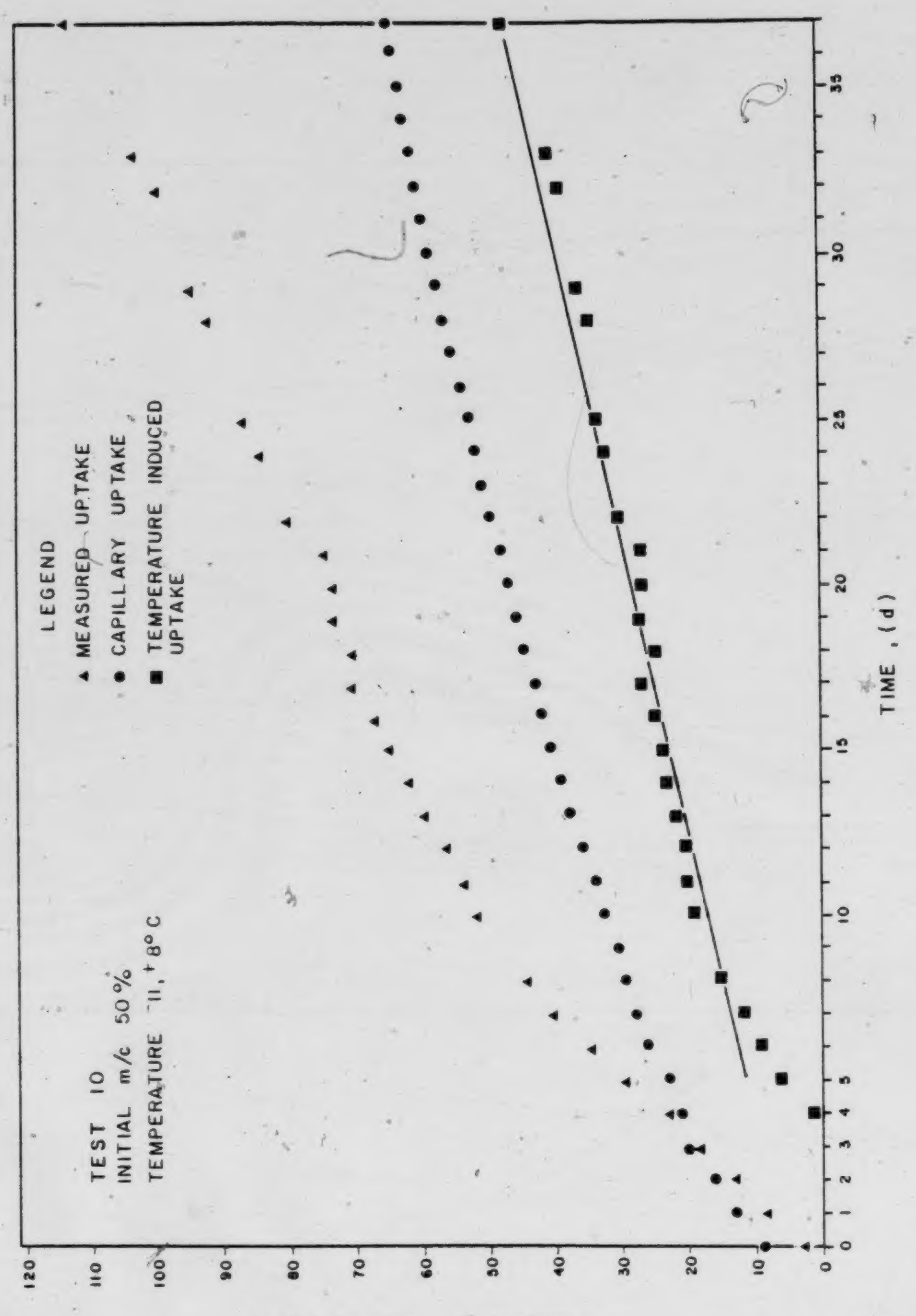


FIGURE 4.23 WATER UPTAKE

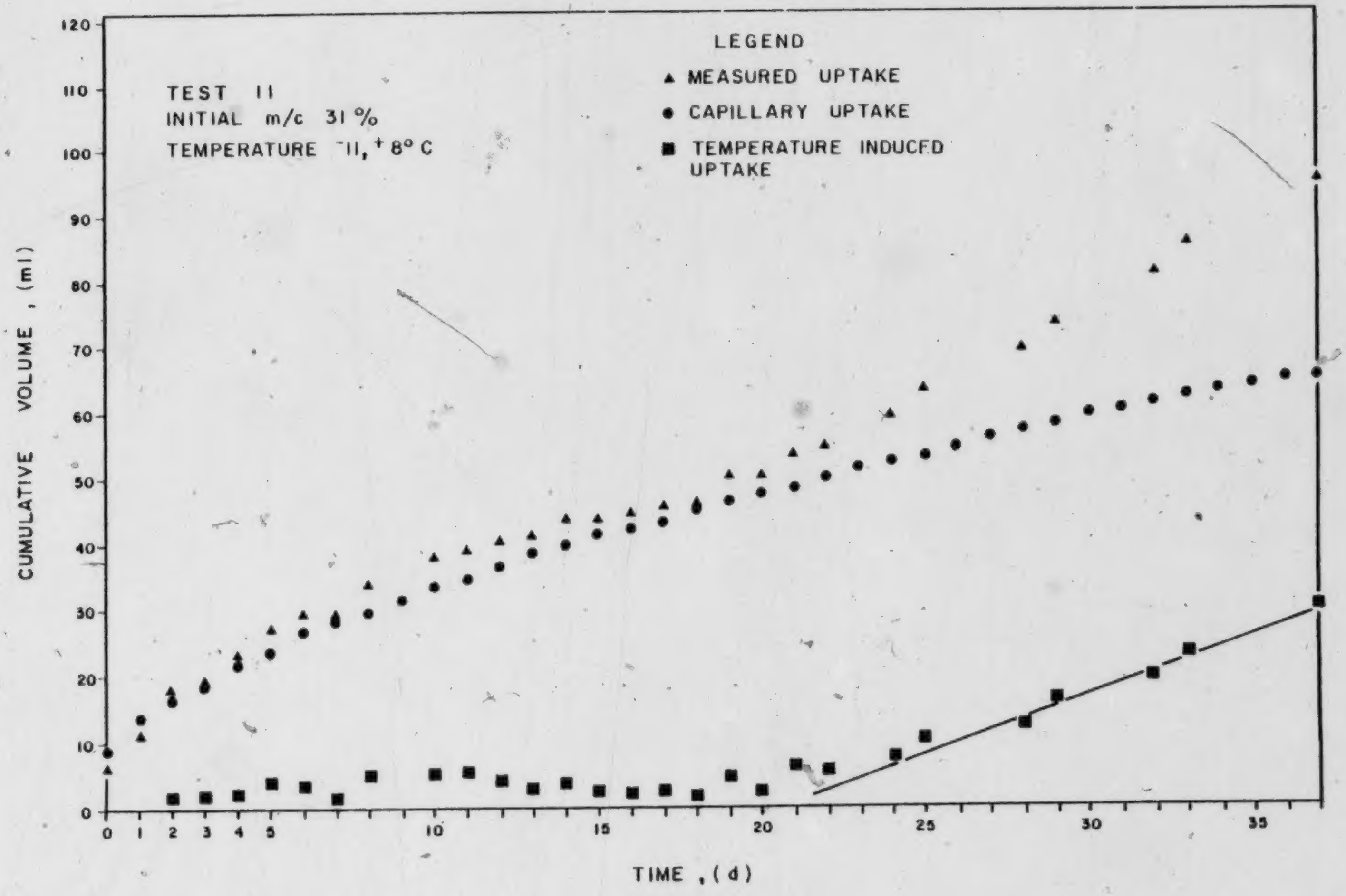


FIGURE 4.24 WATER UPTAKE

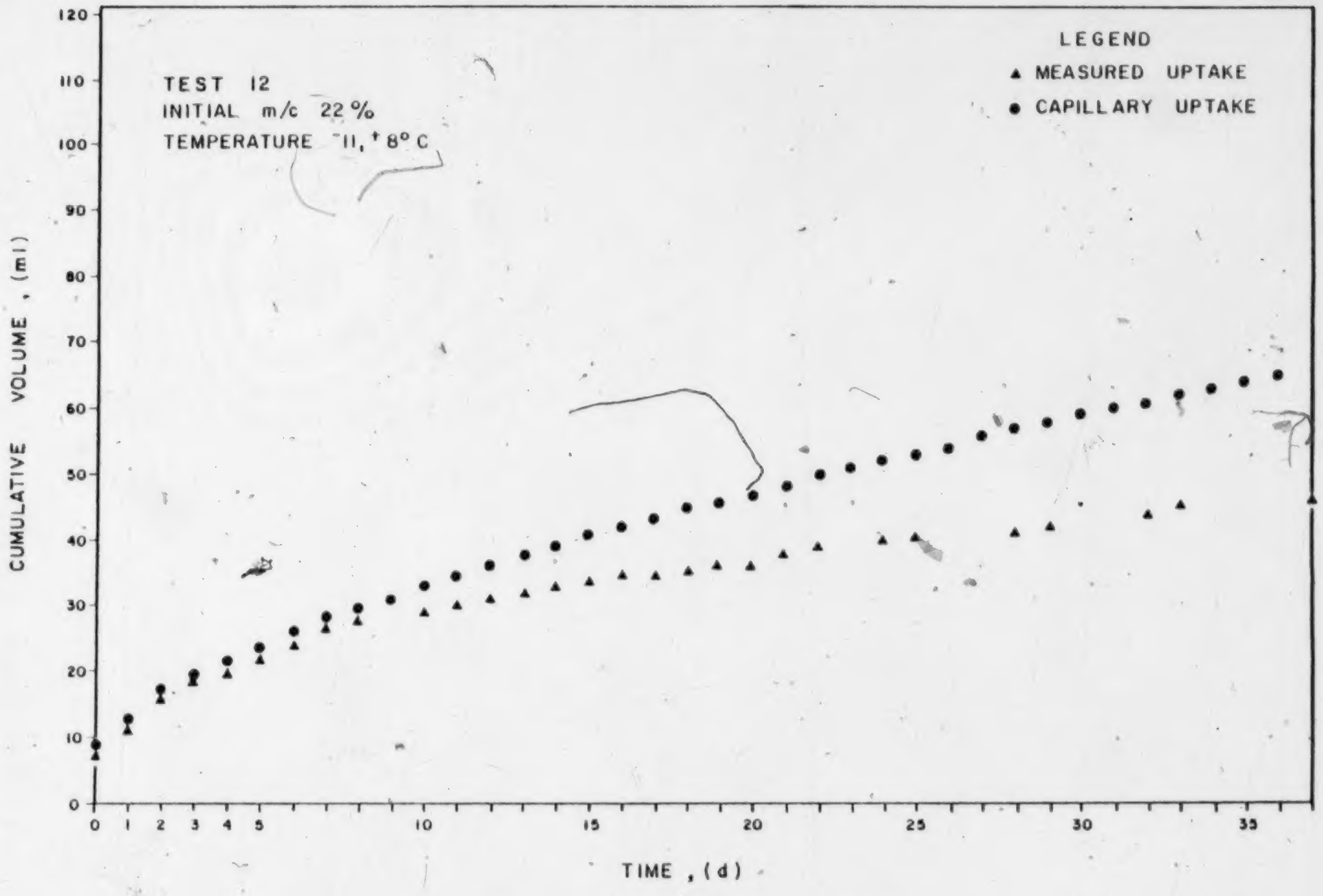


FIGURE 4.25 WATER UPTAKE

TABLE 4.1

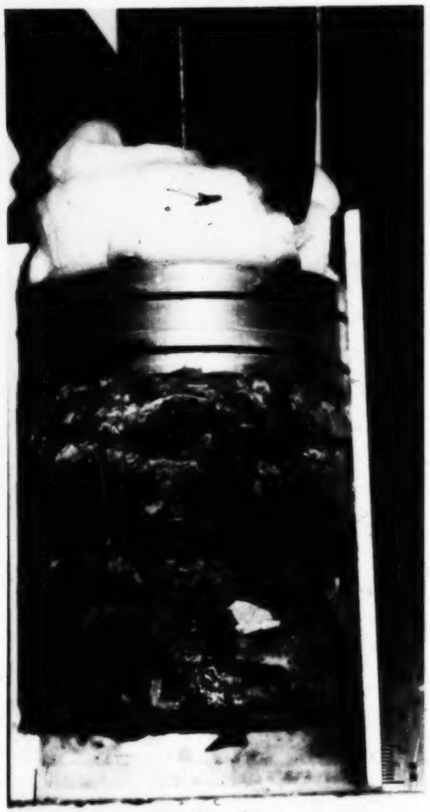
SUMMARY OF TEST RESULTS

Test	Initial Moisture Content (%)	Moisture Content at 0°C Fringe (%)	Wet Density (kg/m^3)	Total Water Intake (ml)	Water Intake Rate, V ($10^{-2} mm^3/s$)	Temp. Grad. Fringe Tf (°C/mm)
1	49	53	798	32	-	0.11
2	49	53	710	92	2.9	0.06
3	49	54	680	57	0.5	0.07
4	53	66	626	137	4.4	0.16
5	53	55	631	90	2.0	0.06
6	53	57	525	77	1.3	0.09
7	27	46	472	89	1.6	0.18
8	30	35	585	79	1.4	0.05
9	50	56	646	101	3.1	0.09
10	50	65	753	108	1.3	0.18
11	31	30	460	96	2.1	0.15
12	22	34	377	46	-	0.17

wetting of the refuse and absorption of moisture by it. At the frost front, ice crystals were observed and generally the ice condition within the voids became more pronounced from the frost front to the cold plate. The zone within approximately 10 mm of the cold plate was ice-rich as shown in Figures 3.12 and 3.13, previously. The top plate acted as an impermeable boundary on which migrating moisture collected. Figure 4.26 shows the various zones, which with slight variation, appeared in all the sample columns at the end of each experiment.

The results shown in the moisture distribution graphs (Figure 4.1 to 4.12) clearly indicate a moisture content increase and a redistribution profile. The maximum increase in moisture content was about 30% for those samples with the lower initial moisture contents. For the samples with the higher initial moisture content, the maximum increase was about 12%. The increase in moisture content at the frost front in all tests ranged from about 4% to about 19%. There was no observable relationship between the magnitude of increase and initial moisture content. The final moisture content profile showed considerable variation from test to test, probably as a result of the non-homogenous sample material.

For those tests with low initial moisture contents, the maximum moisture content occurred at the bottom of the sample and decreased towards the frost front. In the frozen zone it again increased. This is shown in Figures 4.7, 4.8, 4.11, and 4.12 for Tests 7, 8, 11, and 12, respectively. For the tests with the high initial moisture contents, the moisture distribution curves did not show a similar pattern. As shown in Figures 4.1, 4.5, 4.6, and 4.9 for Tests 1, 5, 6, and 9, respectively the final moisture content profile was generally quite


Heavy ice crystallization

Frozen zone. Ice crystals fill the voids

Freeze front location

Dark coloration below the freezing front. Sample gets drier

Bottom 10-20 mm wet

FIGURE 4.26 APPEARANCE OF SAMPLE COLUMN AFTER TESTING

uniform throughout the sample, with some variation of the bottom and top. Figures 4.2, 4.3, and 4.4 for Tests 2, 3, and 4, respectively show the maximum increase in final moisture content to be just below the frost front. Immediately behind the freeze front it decreases rapidly, then shows an increase near the freeze plate. Figure 10 for Test 10, with an initial moisture content of 50% shows a final increase to about 70% in the frost front zone. Below and above this zone the final moisture content shows a fairly uniform decrease.

A study of the total water volume intake for each experiment does not indicate a relationship between it and the initial moisture content, wet density, or temperature gradient at the frost front.

The top and bottom temperatures used were -11°C and +4°C for Tests 1 to 9 and -11°C and +8°C for Tests 10 to 12. The temperature data from the recorder printer was plotted with the moisture profile curves in the moisture distribution graphs, Figures 4.1 to 4.12. Temperature control was not a problem and it was assumed that after stabilization, temperature distribution throughout the sample remained uniform throughout the test and any deviation was not sufficient to alter the interpretation of the experimental results. The temperature data indicated that the samples reached a quasi steady state temperature between 4 to 6 hours after start-up of each experiment.

From the temperature curve, the depth of penetration of the 0°C isotherm can be easily located. The temperature gradient, (°C/mm) at the frozen fringe and for the entire sample column was calculated for each test. The temperature data profile indicates that the frozen fringe is characterized by an almost linear temperature variation with a constant gradient. This characterizes the temperature distribution at the quasi steady state condition. In reality, it is doubtful that the temperature gradient is linear within the frozen fringe, but that the temperature and the thickness of the frozen fringe show constant variations in response to the thermal imbalance during the freezing process. In calculating the temperature gradient at the frozen fringe, a uniform thickness was assumed for all tests.

The temperature profile indicates a non-linear distribution through the sample. The heterogeniety of the sample mixture as well as radial heat flow components could be responsible for the change in slopes of the temperature curve, particularly near the top of the sample.

The temperature distribution affects the length of the unfrozen sample and consequently length of the flow path for moisture to the frozen zone.

Table 4.2 summarizes information related to sample temperature distribution. It is evident that a change in the warm-side temperature from +4°C to +8°C for Tests 10 to 12 did not produce a unique response in the ratio of the length of unfrozen zone to the total sample length. In studying this ratio and the temperature gradient for the sample, it was also evident that there was no clear relationship to the warm-side and cold-side temperatures as was discussed by Konrad (1980) for Devon silt. Such anticipated relationships may be obliterated by the variation in thermal conductivities of various components in the heterogeneous refuse mixture. The ratio of the length of the unfrozen zone to the total sample length varies from 0.29 to 0.77.

TABLE 4.2

SAMPLE TEMPERATURE DISTRIBUTION INFORMATION

Test	Thickness of Unfrozen Zone Luz (mm)	Total Length Of Sample Ls (mm)	$\frac{Luz}{Ls}$	Initial Moisture Content (%)	Control Temperatures (°C)	Temp. Grad. For Sample (°C/mm)	Temp. Grad. (Fringe) (°C/mm)
1	25	85	0.29	49	-11, +4	0.18	0.11
2	70	112	0.62	49	-11, +4	0.13	0.06
3	73	117	0.62	49	-11, +4	0.12	0.07
4	42	82	0.51	53	-11, +4	0.20	0.16
5	80	125	0.64	53	-11, +4	0.11	0.06
6	68	110	0.62	53	-11, +4	0.13	0.09
7	25	82	0.30	27	-11, +4	0.20	0.18
8	86	119	0.72	30	-11, +4	0.14	0.05
9	68	118	0.58	50	-11, +4	0.14	0.09
10	45	95	0.47	50	-11, +8	0.24	0.18
11	86	115	0.75	31	-11, +8	0.20	0.15
12	93	120	0.77	22	-11, +8	0.19	0.17

4.3 Summary

The test result parameters include water intake rate, moisture content profile, and temperature gradient. The water intake rate attributed to the freezing process varied from 0.50 to 4.40 ($x10^{-2}mm^{3}/s$) for the experiments.

The moisture content profile at the end of the tests revealed an increase in moisture content from the initial moisture content which was assumed to be uniform through the entire sample. The moisture distribution profiles, however, do not show any well established patterns for the various zones in the freezing system, i.e., the frozen zone, the frozen fringe, and the unfrozen zone. Samples with the lower initial moisture contents showed a higher moisture content increase and visa versa, at the end of the tests. However, this is a rather precarious conclusion because of the extreme fluctuation in the moisture profiles for tests in the same series, (eg. Tests 1, 2, 3, and 4, 5, 6 which had identical temperature and initial moisture conditions, show sharply varied moisture profiles).

The temperature gradient for the sample columns varied from 0.11 to 0.24°C/mm. The frozen fringe temperature gradient varied from .05 to 0.18°C/mm. In tests 10 to 12 where the warm-side temperature was doubled from +4°C to +8°C, the temperature gradient at the frozen fringe increased as well and was shown to be more uniform at .15 to .18°C/mm than the other tests which showed a variation between 0.05 to 0.18°C/mm. The temperature profiles indicate a rather linear variation through the frozen fringe, while the distribution through the sample column was not linear, particularly near the cold plate.

The ratio of the thickness of the unfrozen zone to the total length of the sample varies from 0.29 to 0.77. There appears to be no relationship between this ratio and the temperature gradient for the sample column, although Tests 11 and 12 do show the highest ratios. This would mean that the 0°C isotherm has shifted upwards in relation to the other tests, which had a cooler warm side temperature.

5. ANALYSIS OF THE FREEZE TESTS

5.1 Water Intake

The water intake flux, V, was taken as the basic freezing parameter. It is the water intake velocity over the cross-sectional area of the sample column. Water intake measurements and the cumulative volume plots in Figures 4.13 to 4.24 reveal that there are two rates of intake. For the first three to five days there is an increased rate followed by a dampening effect. This may be the result of a diminishing moisture gradient as the unsaturated conductivity of the refuse increased (the tension head would become less negative). At any rate, the analysis of the freeze tests led to the search for a relationship between this basic parameter and other variables such as initial moisture content, density, temperature gradient, or unfrozen sample length. Plots of this data, however, fail to define a clear relationship.

Inspection of the moisture distribution graphs in Figures 4.1 to 4.12 indicate a maximum moisture content increase of approximately 30% for samples with the lower initial moisture contents and approximately 12% increase for those samples with the higher initial moisture contents.

In all four series of tests there was a water intake flux to the sample which was attributable to the freezing process (tests 1 and 12 were exceptions). This is the important experimental result, since it was this parameter that was basic to the scope of this study. The parameter which is considered to characterize the relationships between the derived parameters of water intake flux and temperature gradient is segregation potential.

5.2 Segregation Potential

As discussed in Section 2.4.5, the characteristics of a freezing soil can be represented by the segregation potential, SP, defined as the ratio of the rate of water migration, V, and the overall temperature gradient in the frozen fringe, grad Tf, at any time, t, (Konrad, 1980):

$$SP(t) = V(t)/\text{grad } Tf(t) \tag{5.1}$$

The water intake flux, V, is the water intake velocity over the cross-sectional area of the sample column. The temperature gradient at the frozen fringe, Tf, is easily calculated from the temperature profiles in the moisture migration graphs. Table 5.1 presents the segregation potential, SP, calculations.

The segregation potential is related to the suction force at the frozen fringe and is a function of the degree of thermal imbalance (Konrad, 1980). The segregation potential will therefore vary with quasi-steady state conditions such as during the advance of a frost front.

In all tests, during the application of a temperature gradient, the temperature conditions remained unchanged during the test duration, therefore the anatomy of the frozen fringe is assumed to be constant (a temperature gradient was not applied to Tests 7, 8, and 9 until after 18 days). For simplicity, since geometrical and thermal boundary conditions were not imposed, it is assumed that the frozen fringe thickness is fully developed and defined shortly after temperature stabilization through the sample. In calculating the temperature

TABLE 5.1

SEGREGATION POTENTIAL (SP) ANALYSIS

Test	Steady-State Water Intake Rate, V ($mm^3/s \times 10^{-2}$)	Temp. Gradient At Freeze Fringe, grad Tf (°C/mm)	Segregation Potential, SP ($10^{-5} mm^2/s \cdot °C$)
1	-	0.11	-
2	2.9	0.06	6.0
3	0.5	0.07	0.8
4	4.4	0.16	3.5
5	2.0	0.06	4.2
6	1.3	0.09	1.8
7	1.6	0.18	1.1
8	1.4	0.05	3.4
9	3.1	0.09	4.3
10	1.3	0.18	0.8
11	2.1	0.15	1.7
12	-	0.17	-

gradient at the frozen fringe from the temperature profile curve of the moisture distribution graphs an equal increment of 10 mm behind the 0°C isotherm was used.

The water intake rate, V, was determined for the freezing process alone by subtracting capillarity values from the total measured values. Therefore, the water intake rate used in the calculation subtracted the effect of water intake flux induced by capillary action alone. Tests 1 and 12 did not permit a calculation since the water intake velocity did not exceed the rate attributed to capillary action alone.

The interpretation of test results in terms of measured parameters such as water intake flux, gradients, and length of the unfrozen soil sample has shown to be meaningless. It is thought that the results are very sensitive to the freezing procedure and the quasi-steady state conditions developed for the samples. The mere heterogeneity of the sample material would have a strong effect on these processes.

Two test control variables which are not related by segregation potential are initial moisture content and in-situ sample density.

Data analysis fails to show any clear relationship between calculated segregation potential and initial moisture content of the samples. The initial moisture content for the four series of tests varied from 22% to 53%.

The other test parameter, wet density, does show a relationship with SP although there is considerable scatter from a straight-line relationship as shown in Figure 5.1. Two points on the plot for Test 3 and 10 show extreme scatter from the remainder. If these are ignored,

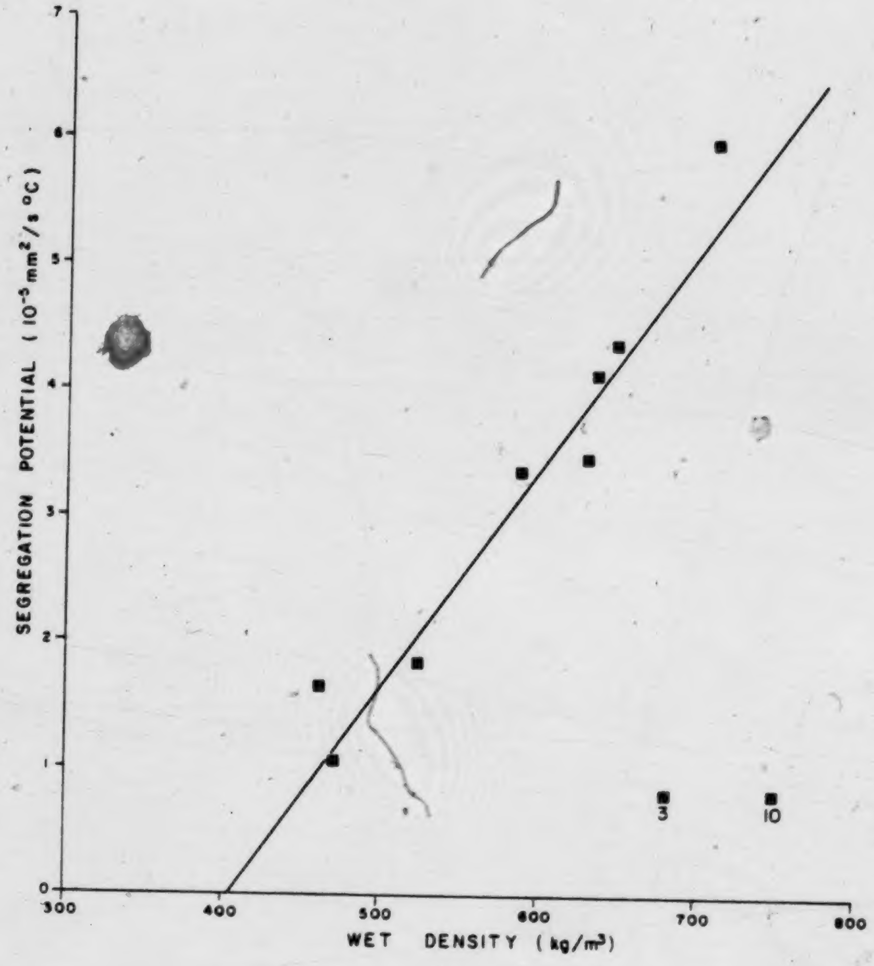


FIGURE 5.1 . SEGREGATION POTENTIAL - WET DENSITY RELATIONSHIP

the remaining 10 tests do signify that a relationship between SP and in-situ wet density does exist.

5.3 Summary

The four series of laboratory experiments have demonstrated that the freezing process is capable of causing water migration from a free supply through the refuse sample towards the freeze front. Moisture initially present in the refuse may also become redistributed as a result of the thermal gradient. The parameter of segregation potential provides a basis for coupling mass flow with heat flow in a freezing soil and has been applied to characterize the relationship between water intake flux and temperature gradient for a refuse medium.

Analysis of test results shows that there is no clear relationship between segregation potential and derived parameters such as water intake flux, temperature gradients and length of the unfrozen sample.

It appears that there is a relationship between segregation potential and sample density. As the wet density increased in the range of 450 kg/m^3 to 700 kg/m^3, the segregation potential increased ten fold from $0.8 \times 10^{-5} mm^2/s \cdot {}^\circ C$ to $6.0 \times 10^{-5} mm^2/s \cdot {}^\circ C$.

It becomes apparent therefore, that the thermal gradient can be an effective driving force for moisture migration within the refuse material.

6. DISCUSSION

6.1 Leachate Generation by an Unsaturated Sanitary Landfill

In an area of semi-arid climate, where evapotranspiration commonly equals or exceeds precipitation, the landfill environment is characteristically in an unsaturated condition. The generation of leachate by an unsaturated sanitary landfill depends on the moisture content within the landfill, its distribution, and its variation with time. Leachate volume is therefore determined by two conditions:

1) the availability of water; and
2) the hydraulic transmission phenomena within the landfill environment.

The influence of changes in climate and season play an important role in altering these conditions. The following discussion details these conditions as a prerequisite to establishing the significance of a thermal gradient in the leachate production process within a sanitary landfill.

6.1.1 Sources of Water

All sources of water must be considered important in the leachate production process. To recapitulate, these include:

1) initial moisture content of refuse;
2) metabolic water from decomposition (includes release of adsorbed water during stabilization);
3) infiltration water due to rainfall and groundwater; and
4) artificially added water.

A simple mass balance as shown in Figure 6.1 (revised from Metry and

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Figure 6.1 (Metry and Cross Jr., 1976) has been removed from the text due to copyright restrictions. It depicts a mass balance relationship within a municipal landfill.

Cross Jr., 1976) effectively demonstrates the leachate production process. All types of waters identified by a plus sign are contributing factors to leachate generation, while those flows identified by a minus sign represent factors that reduce the potential of leachate generation. Leachate quantity, Q_L, is the balance of the sum's: input minus output. For purposes of this analysis, a source not included in the mass balance is the artificially added water. If one assumes that all surface runoff from adjacent areas is diverted around the landfill surface, then the term, Q_{RL}, would become negligible as well.

From this analysis, it can be seen that precipitation, groundwater intrusion, and metabolic water from waste decomposition represent the water inputs (assuming runoff is diverted and neglecting artificial addition).

In much of the literature, little consideration has been given to water of decomposition since the amount considered is minimal considering the large amounts that may be contributed from infiltrating precipitation. Where percolation through the landfill is minimal from infiltration, as in semi-arid climates or during winter months, this may be a major source of leachate. The water of decomposition could be a major contributor towards saturation of the refuse, with additional percolation resulting in leachate generation. Also, during decomposition or refuse stabilization, there is a release of adsorbed water which minimizes the water holding capacity of the refuse. Such a situation would be typical of a winter to spring seasonal change, resulting in an annual cycle of leachate production with peak flows in the spring.

Ludwig (1961) calculated the water of decomposition to be 34 mm/m of fill depth [34mm $(1/m^3)$ $(1/m^2)$] with an upper limit of 84 mm/m of fill depth. The significance of this becomes apparent in consideration of the water holding capacity or the field capacity of refuse and soils.

The contribution of moisture from the ground water table may become an important element where the landfill base is in contact or in close proximity to that source. The capillary potential gradient along with the thermal potential gradient studied in this thesis may be large and may control the flow throughout most of the moisture content range (saturated and unsaturated).

6.1.2 Moisture Movement Through Refuse

The moisture transmission phenomena within the landfill are determined by definite properties of the refuse, cover, and surrounding earth.

A question that must be considered in defining the behavior of moisture movement through refuse is how closely does it resemble a normal porous medium. As deposited in a fill, it is extremely non-homogeneous. Aside from the variations in composition within a landfill, it is not certain that moisture movement obeys the same laws as those known suitable for granular material. It seems probable that refuse in general, and particularly combustible rubbish will have pore sizes distributed about two vastly different orders of magnitude. These will be (1) the interstices of the individual objects which comprise the refuse, namely paper, plant tissue, textiles, and other porous material; and (2) the much larger voids scattered among the conglomerate of the component objects (Ludwig, 1961). The finer pores will exhibit the phenomena associated with capillarity-retention of water, transmission toward decreasing moisture content in all directions, and low hydraulic conductivity. The large voids will behave either as channels or air pockets depending on whether they are or are not interconnected. Ludwig (1961) concluded that if the foregoing hypothesis is correct, refuse should behave as fine-grained porous medium until the small scale pores in any portion of it become saturated. After this, there will be a large apparent increase in hydraulic conductivity as water begins to fill the large voids and flow through them. From this, it can be assumed that the hydraulic characteristics of the soil and the refuse mass are uniform in all directions.

A slug of moisture having penetrated into the refuse medium by infiltration from a saturated surface thereafter diffuses outward into the surrounding drier regions and also moves downward under gravity. The amount of water available for percolation, and consequently for leachate generation, will be determined by the capacity of the soil and the refuse to store water. This is known as the field capacity and is the moisture content to which the medium will drain under the influence of gravity. Qasim and Burchinal (1970) reported an average field capacity for refuse of 135 mm/m of refuse in three experimental tests. Ludwig (1961) reported a value of 200 mm/m of refuse just before moisture release (stabilization process) and 62 mm/m of refuse afterward. Field capacities computed from input/output moisture data from various studies indicate different values among experimental research, generally ranging between 300 mm/m and 400 mm/m.

The amount of water that can be added to refuse before reaching field capacity depends on the moisture content of the waste at the time of placement in the landfill. Obviously, moisture content is not a constant, but it is a function of waste composition, processing, and climatic conditions. The refuse field capacity probably changes during its life cycle. The refuse field capacity and initial moisture content are at best, only reasonable approximations due to the material's heterogeneous nature. As a rule of thumb, however, moisture content of the refuse at the time of placement has been found to range from 20% to 30% and field capacity to range from 30% to 45% (by volume, wet mass basis). If initial moisture content is 30% and the field capacity is 40%, this suggests that the buried waste will absorb 100 mm of water per unit mass, before leachate is produced. In this instance, if the water of decomposition as reported earlier, is as high as 84 mm/m, this source of water would play a significant role in leachate production.

For continuous vertical drainage to occur away from the landfill, the soil zone beneath the landfill must also reach its field capacity.

Leachate percolation can occur by channelling through the refuse, whereby the moisture flows through openings or channels before the refuse has reached field capacity. This is also true for soils where intergranular flow is established through fractures.

Rovers and Farquhar (1973) and others have reasoned that the amount of moisture entering the refuse mass and the amount of leachate discharging exist in a one-to-one relationship after the refuse has reached field capacity. Although this would seem logical, effects of channelling should be recognized as possibly increasing the amount of moisture retained.

6.2 Transient Moisture Behavior

It has generally been accepted that the behavior of moisture in a landfill follows the physical laws of flow in an unsaturated porous medium as described by Darcy's law. In this case, there are two gradients considered - the gravitational potential and the capillary potential. Moisture movement is by gravity drainage and diffusion.

It has been shown by the results of this experiment that a temperature gradient across a refuse sample will induce moisture movement from the lower layers towards the location of the frost front. The magnitude of this increase ranged from 12% to 30% over the length of the sample, depending on the initial moisture content. It has been established by other researchers that the driving force for this water migration is the suction potential at the frost front as shown in Figure 6.2 (Konrad and Morgenstern, 1983).

The significance of this transient moisture behavior over seasonal changes becomes apparent in the leachate production process. Assuming a conservative approach by considering a semi-arid climate such as in Alberta, this may be the main leachate producing mechanism. To demonstrate, one may consider a completed landfill in an active state (i.e., aerobic and anaerobic decomposition proceeding). During late fall the surface cap begins to freeze and by middle to late winter, the frost front has penetrated into the top portion of the refuse mass. During this time no moisture infiltration has occurred and because of the semi-arid climate, infiltration has been minimal throughout the previous summer. With mass flow created by the freezing process, moisture will move upwards towards the frost front where it will accumulate as ice lenses. This moisture would move from any available

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Figure 6.2 (Konrad and Morgenstern, 1983) has been removed from the text due to copyright restrictions. It depicts the frozen fringe in freezing soils.

sink including channels, large voids, and possibly the ground water table, particularly if it is connected to the base of the landfill. The water of decomposition would also contribute to this flux activity.

It is conceivable that a zone of saturation may be created within the fill depth by this moisture migration. In the spring, thaw would create precipitation and infiltration would add a slug of moisture to the landfill. This contribution would further enhance the moisture content of the refuse with the possibility of attaining field capacity and subsequently becoming a leachate plume which would move vertically and horizontally through the landfill. Depending on the hydraulic and the physical conditions in the lower portions of the landfill, this slug of leachate may find its way to the base.

Under extreme conditions of deep frost front penetration and a water supply at the base of the landfill, the moisture migration flux could possibly create field capacity conditions between the frost front and the water table. During thaw, the leachate would drain to the water table.

7. CONCLUSIONS

It would be useful to review the factors within a landfill environment which would play an important role in the concept of thermally induced moisture migration. Basically, these factors would relate to segregation potential and the suction force(s) at the frost front.

The temperature gradient across the landfill mass would affect the location of the frost front as well as the thickness of the frozen fringe and the temperature gradient at the frozen fringe. Therefore, the ambient air temperature during the frost season as well as the temperature within the landfill would be critical factors. The age of the landfill would affect the temperature within the landfill through the decomposition process. The temperature distribution would also affect the depth of unfrozen fill. The length of the moisture flow paths would determine the magnitude of suction potential at the freeze front.

Another significant factor would be the permeability of the frozen mass. Konrad (1980) had shown that there was a distinct relationship between permeability of the frozen fringe and the suction at the frost front for soil conditions. Permeability would also determine the effectiveness of the frozen layer to act as an impeding layer to moisture flow. This would affect the thickness of the zone of moisture accumulation and possibly the degree of ice lensing.

From the experimental results, it appears that the density of the landfill mass would affect the segregational potential. The higher the in-place density, the higher the segregation potential.

Apart from these factors, the hydraulic characteristics of the landfill mass and the physical properties of the medium would affect the moisture regime within the landfill including the aggregate field capacity behavior.

Based on limited experimental results this study has revealed that the concept of thermally-induced moisture migration is applicable to a refuse medium. The results demonstrate the feasibility of analyzing compacted solid waste as an unsaturated porous medium. The relevance of this concept to a cold-region sanitary landfill environment is in the leachate production process - leachate quality and quantity result from the interaction of fundamental transport phenomena within specific physical and environmental settings.

The segregation potential provides a basis for coupling mass flow with heat flow in a freezing soil and has been applied in the study of frost action and problems resulting from frost damage in soils. This freezing parameter has been applied in one-dimensional laboratory freeze tests associated with a "quasi" stationary frost front.

From a phenomenological point of view, cyclic freezing and thawing of a landfill surface creates a modus operandi for this freeze parameter and results in seasonal moisture flow resulting in a potential for creating moisture sinks and slug flow conditions within the landfill refuse mass. The implications of such hydraulic conditions would have an important impact on the leachate production processes (as they are now understood) and particularly on seasonal peak leachate production periods.

Additional experimental work is required in order to identify and refine the description of this moisture transport phenomena. Ultimately, a porous medium-based laboratory model could be applied to field-scale problems.

8. RECOMMENDED RESEARCH

The principal types of data lacking for a confident appraisal of effects associated with the hydraulic characteristics of a landfill are the moisture transmission characteristics of the refuse. As with much of laboratory research there is an inherent problem in applying this research to field conditions, and that problem is one of scale-up complexities. Refuse moisture transmission characteristics, temperature profile conditions, and leachate production mechanisms can vary considerably from the laboratory to the field and much field data is needed to provide a better insight and understanding into scale-up problems. Some specific evaluations pertaining to moisture characteristics of refuse could include:

1) The moisture holding capacity (field capacity) of compacted refuse in its original and decomposed states.
2) The moisture profile within a refuse cell during infiltration, including observation of its uniformity.

This data would be most meaningful if obtained from actual fills or portions of fills, with controlled moisture application. This could be achieved by pilot-plant type experiments.

Other data would be meaningful in establishing the significance of cold season temperatures in creating a thermal gradient through the landfill. This information could easily be obtained by installing temperature probes at different depths and locations within a landfill.

In relation to a thermal response, a suction moisture content curve should be determined for a completed fill. This could be accomplished by the use of moisture sensing devices, perhaps supplemented by lysimeters, throughout the fill depth. This data should be obtained for numerous freeze-thaw cycles. It may also be meaningful in studying the capillary conductivity of the refuse material.

Basic to all the aforementioned would be a measurement of leachate quantity produced. This data could be collected from pilot plant test cells which would be subjected to carefully controlled conditions of moisture application. For comparison, one cell could be provided with a supply of water at or very near to its base (simulated ground water table). Data would be collected monthly over numerous freeze thaw cycles.

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APPENDIX A

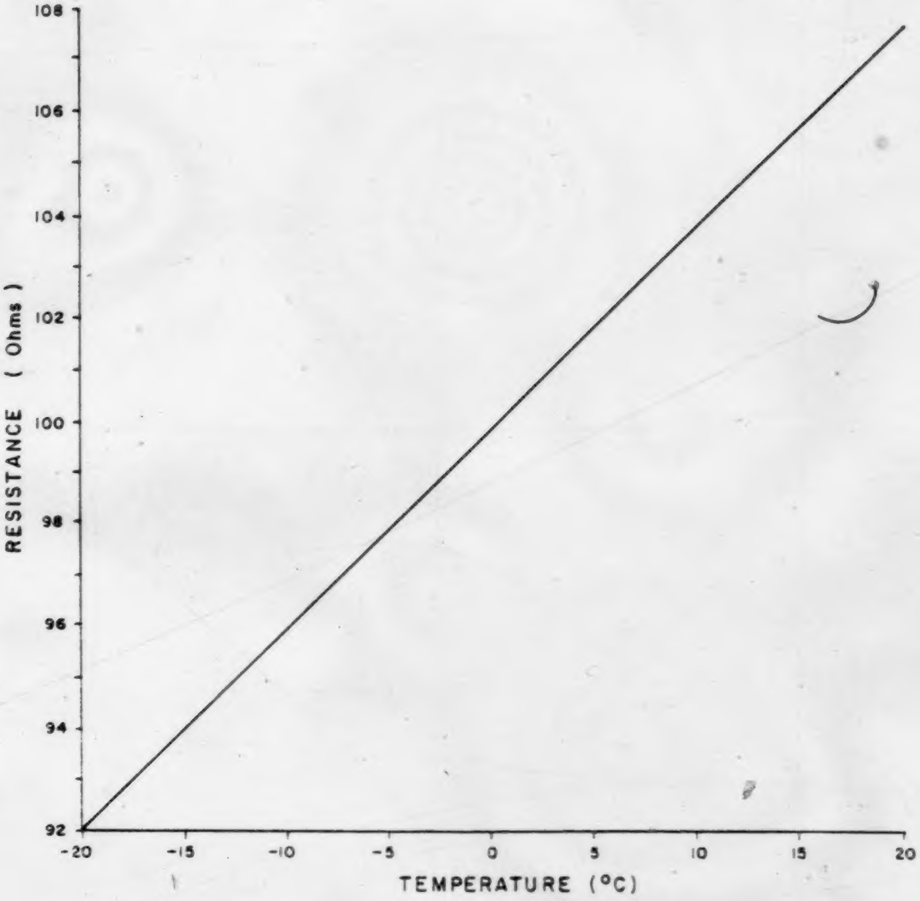

FIGURE A_1. CALIBRATION LINE FOR RTD's.

APPENDIX B

Tests For Moisture (Water)

There are three methods of making moisture tests: (1) oven drying; (2) infrared; and (3) toluene distillation. The oven drying method is most used because it is more accurate than the others and is a step in the preparation of samples for subsequent analyses. It should always be used in perference to the other tests unless it is necessary to get an answer rapidly and it is not necessary to have complete accuracy.

Oven Drying Method

Equipment: Drying oven, preferably with forced air circulation; large desiccator jar or cabinet and desiccant; sample containers (covered aluminum cans about 3½ inches in diameter and 2 inches deep have proven satisfactory); triple beam balance graduated to 0.1 grams (an analytical balance is satisfactory if it has a capacity of 200 grams).

Procedure: Duplicate samples of 50 to 100 grams of fresh ground refuse, compost, or other organic wastes are taken in tared sample containers and immediately covered. Inorganic materials such as glass, metal, and ceramics a ½-inch or larger are discarded. Material should not be packed down. Samples should be weighed to the nearest decigram within an hour and dried to a constant weight in drying oven at 75°C with lids cocked or off. With samples of less than 60 per cent moisture content, drying for 24 hours in a forced air oven may be sufficient; 48 hours are preferred. Drying at 75°C is preferable to drying at 103°C because it permits retention of more of the volatile constituents other than water (particularly ammonia-N and lipids). With materials containing free liquid (70 to 75 per cent or more water) such as raw garbage or sewage sludge, most of the water may be evaporated first on a steam bath, with final drying in the oven. The sample is then cooled in a desiccator jar or cabinet with lids on, and it is weighed.

$$\text{Calculation:} \quad \frac{100\ (\text{loss in weight})}{(\text{net wet weight})} = \%\ \text{moisture (wet basis)}$$

The value is approximately equal to percent water by weight and should not be confused with per cent liquid.

APPENDIX C

Test For Volatile Solids and Ash

Equipment: Drying oven, analytical balance; desiccator jar; porcelain crucibles, high form No. 1, 1A, or 2; muffle furnace with indicating pyrometer and rheostat temperature control.

Procedure: Transfer 3 to 6 grams of dried and ground sample to a previously ignited and tared crucible. Redry for 2 hours at 75°C and obtain sample weight directly to nearest centigram. Place the crucibles in a cold sample weight directly to nearest centigram. Place the crucibles in a cold muffle furnace and gradually bring the temperature to 600° to 650°C with the door raised about ½-inch. Muffle at this temperature for 2 hours; cool in desiccator and weigh.

Calculation: $$\frac{100\ \text{(loss in weight)}}{\text{(net dry weight)}} = \%\ \text{volatile solids}$$

This value approximates the per cent organic matter of the material. The value for per cent ash is 100 minus per cent volatile solids.